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PROVISIONAL SPECIFICATION

Invention Title Counter-Propagating Signal Method for Locating Events in Fibre Optic Sensor Systems

The invention is described in the following statement:

COUNTER-PROPAGATING SIGNAL METHOD FOR LOCATING EVENTS IN FIBRE OPTIC SENSOR SYSTEMS

FIELD OF THE INVENTION

This invention relates to a waveguide transmissive counter-propagating signal method and associated systems for locating events in fibre optic sensing systems.

ART BACKGROUND

Optical devices are commonly used in industry and science and include laser cavities, waveguides, lenses, filters and other optical elements and their combinations. Such optical devices are used in a variety of instruments and installations.

Photonics technology has revolutionised the communications and sensor fields. This is mainly due to the rapid development of optical and opto-electronic devices. A wide variety of glass materials, material-dopants and waveguide structures are available and this provisional specification relates to a waveguide transmissive counter-propagating signal method and associated systems for locating events in fibre optic sensing systems.

Presently, there is a very high demand for sensors and systems that provide real-time monitoring of the integrity or condition of machines and structures. Fibre optic sensors, in particular, are very promising for these applications because of their dielectric properties, their fine size, their ability to be remotely located and, in the case of intrinsic sensors, rapid response times. They also have particular advantages in hazardous environments. In addition, they have several clear advantages over existing conventional sensing techniques such as bulk optical measurements, potentiometric electrodes, resistive foil gauges and piezo-electric transducers.

Engineered structures are usually not monitored in real-time because of the difficulties in incorporating conventional sensors into the sensing environment and because of the limitations of the sensors. Furthermore, conventional sensors are generally point sensing devices, thus requiring a large number of sensors to cover a large area or long length of interest. The subsequent cost and complexity of such a system is most often impractical.

Fibre optic sensors overcome many of these difficulties by virtue of their inherent properties. In addition, optical sensors and optical processing systems are extremely fast and do not suffer from electro-magnetic interference (EMI), unlike their electronic counter-parts. The technology is gaining wide acceptance for monitoring applications and is expected to play a major role in the realisation of real-time structural integrity and machine condition monitoring systems, offering an advanced new generation of engineering sensors.

Fibre optic sensor technology has progressed at a rapid pace over the last decade. Many different sensing techniques have been developed to monitor specific parameters. [1] Different configurations of fibre sensing devices have been developed for monitoring specific parameters, each differing by the principle of light modulation. Fibre optic sensors may be intrinsic or extrinsic, depending on whether the fibre is the sensing element or the information carrier, respectively. They are designated "point" sensors when the sensing gauge length is localised to discrete regions. If the sensor is capable of sensing a measurand field continuously over its entire length, it is known as a "distributed" sensor; "quasi-distributed" sensors utilise point sensors at various locations along the fibre length. Fibre optic sensors can be transmissive or can be used in a reflective configuration by mirroring the fibre end-face. So, fibre optic sensors are actually a class of sensing device. They are not limited to a single configuration and operation unlike many conventional sensors such as electrical strain gauges and piezoelectric transducers.

However, to-date most fibre optic sensor systems are based on point sensing devices, thus again requiring a large number of sensors to cover a large area or long length.

Very few distributed techniques have been developed and are commercially available. [2,3] Of those that have been developed, fewer still have the capability to actually locate the region or position of the sensed parameter or disturbance along the fibre length; they simply detect, alert and sometimes quantify that an event has occurred.

Methods devised in the prior art for distributed sensing that are capable of locating the position of the sensed parameter include:

- Most current techniques for monitoring fibre optic cable integrity are based on static or slowly varying measurements employing optical time domain reflectometry (OTDR) [4] (ie., sharp bends, fibre fracture, fibre attenuation, connector losses, etc.). This method is essentially based on an optical radar technique, where a very narrow pulse of light launched into an optical fibre is back-scattered or back-reflected by anomalies in the fibre material or structure along its length (ie., fracture, localised compression, fault, etc.) and the measured time-of-flight determines the locations of the anomalies.
- Fibre Optic Distributed Temperature Sensor (DTS) systems have been developed for continuous temperature measurements along the entire length of an optical fibre, and any surface or structure which the fibre is attached to. In the majority of distributed temperature sensing, the ratio of the intensity of the Stokes and anti-Stokes return signals are measured in an optical time domain reflectometry (OTDR) configuration. [5-8] The end result is a true measurement of the temperature profile along the entire length of the sensor.
- Various OTDR back-scattering techniques for strain and pressure measurements have also been investigated, although no commercial technology is yet available. [3,9,10]
- Physical placement of Sagnac interferometer loops at specific locations or geometric configurations have also been used for distributed fibre disturbance detection and location. [11,12] In a Sagnac interferometer, light is launched into opposite ends of a sensing fibre loop such that two beams circulate through the loop in opposite directions and then recombine to produce a phase interference pattern on a single photodetector. No use of the time of travel or time delay between the counter-propagating signals is used in these methods.

The most common methods for locating events are based on techniques using the back-scattering or back-reflection of extremely narrow pulses of laser light, combined with some other form of sensing mechanism to extract further information about the actual sensed parameter (ie., temperature, strain, pressure, etc.). However, while modern advances in photonics devices have allowed very precise and accurate systems to be developed and commercialised, they are often very complex and expensive. The main reasons for the complexity and high cost of these units is largely in the requirement for very high accuracy and high speed components needed in order to generate extremely narrow pulses of laser light, detect optical signals of extremely low power (often this involves photon-counting and significant averaging of the signals [13]), and provide extremely accurate timing for the time-of-flight measurements of the light pulses.

Owing to the requirement of measuring and averaging the time-of-flight of very narrow, low power pulses, these techniques are often limited to monitoring static or very slowly varying parameters. In addition, to-date most systems based on this principle monitor only temperature. However, they do offer one significant advantage over most other techniques, including that contained in the subject of this provisional patent application; namely, the ability to provide the profile of the sensed parameter along the entire length of the fibre.

Nevertheless, it would be a significant advance to be able to also obtain real-time, quasi-static and dynamic information about any form of disturbance to the optical fibre, particularly transient events which are too quickly occurring to detect with OTDR techniques. This can be achieved by combining a distributed sensing technique incapable of locating the events with a compatible technique which is capable of locating the events. This would have the further advantage of monitoring any structure or material near the fibre or to which the fibre is attached. Such a capability should enable truly distributed sensing applications such as structural integrity

monitoring, pipeline leak detection, ground monitoring, machine condition monitoring and intrusion detection of high security areas.

The object of the present invention is to provide a waveguide transmissive counter-propagating signal method and associated systems for locating events in fibre optic sensing systems. While this technique may not provide the profile of the sensed parameter along the entire fibre length, it enables dynamic and transient events to be located in virtually any distributed fibre optic sensing system, and its transmissive counter-propagating technique does not possess the limitations and complexities of OTDR principles.

The four main innovative features of the invention are:

- Operates on virtually any existing type of transmissive distributed fibre optic sensor, enabling dynamic and transient events to be detected, quantified and located anywhere along the length of the optical fibre.
- Operates in a transmissive configuration, thus delivering the entire optical signal and power back to the detector and not requiring signal averaging.
- Determines the location of events via the time delay measured between counter-propagating optical signals effected by the same disturbance. This may require the sensing technique to be modified into a loop configuration.
- Does not require laser pulsing, although it is capable of operating with pulsed techniques.

Example of non-locating distributed fibre optic sensing techniques which the present invention could be compatible with, without imposing any limitations, include: [1-3]

- Modalmetric interferometers [14-16]
- Sagnac interferometers
- Michelson interferometers
- Long-length Fabry-Perot interferometers
- Mach-Zehnder interferometers
- Two-mode interferometers

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BRIEF SUMMARY OF THE INVENTION

The object of the present invention is to provide a waveguide transmissive counter-propagating signal method and associated systems for locating events in fibre optic sensing systems.

The present invention relies on the measurement of the time delay or difference between transmissive counter-propagating optical signals affected by the same event in an optical loop arrangement. In this novel arrangement, continuous-wave (CW) optical signals are simultaneously launched, preferably from a single light source, into opposite ends of a sensing optical fibre or set of fibres and simultaneously detected by photodetectors. Pulsing of the optical signal is not necessary, although it may be employed in some arrangements. Any sensed parameter which acts to alter the counter-propagating signals will effect both signals in the same manner, but because the effected counter-propagating signals must each continue travelling the remainder of the fibre length to their respective photodetectors there is a resultant time delay or time difference between the detected signals. The time delay is directly proportional to the location of the sensed event along the fibre length. Therefore, if the time delay or difference is detected and measured, the location of the event can be determined. At the same time, if a compatible sensing mechanism is being employed the sensed event can be quantified and/or identified (ie., strain, vibration, acoustic emission, temperature transient, etc.). In addition, non-sensitive fibre optic delay lines may be connected to the sensing fibre at either or both ends in order to add additional delay between the transmissive counter-propagating signals and to provide insensitive lead fibres. This may assist engineering the technique into a practical working system.

The main features of the present invention, without imposing any limitations, involve:

- Operating in a transmissive configuration, thus delivering the entire optical signals and power back to the respective detectors and not requiring signal averaging.
- Determining the location of sensed events via the time delay measured between counter-propagating optical signals effected by the same disturbance.

The present invention may be said to reside in a waveguide transmissive counter-propagating signal method and associated systems for locating events in optical waveguides including:

- a light source;

- a silica waveguide for receiving light from the light source from both ends of the waveguide, the silica waveguide being capable of having the counter-propagating optical signals or some characteristic of the light modified or effected by an external parameter, such that the parameter may be quantified and/or identified; and
- detector means for detecting the counter-propagating optical signals effected by the same parameter and for determining the time delay or difference between the signals in order to determine the location of the sensed event.

Preferably further silica waveguides are connected to the sensing waveguide at either or both ends in order to add additional delay between the transmissive counter-propagating signals and to provide insensitive lead waveguides.

Preferably the detector means comprises:

- first and second photodetectors for simultaneously receiving the radiation from the counter-propagating signals in the silica waveguide; and
- processing means for receiving signals from the first and second photodetectors for determining the time delay or difference between the signals effected from the same disturbance and therefore determining the location of the sensed event.

Preferably a waveguide coupler or set of couplers is arranged between the light source and photodetectors and the silica waveguide so that the light can be simultaneously transmitted from the light source to both ends of the silica waveguide and the detector means also being connected to the coupler or couplers so that the counter-propagating transmissive radiation can be directed via the coupler or couplers from the silica waveguide to the detector means.

The preferred embodiment provides a waveguide transmissive counter-propagating signal method and associated systems for locating events in optical waveguides, which may include:

- providing an optical fibre (single or multi moded) formed from a waveguide material designed to simultaneously transmit counter-propagating optical signals;
- providing a sensor configuration (single or multi moded), with any appropriate waveguide length, any suitable geometry and compatible with the waveguide transmissive counter-propagating signal method and associated systems for locating events in optical waveguides, designed to optimise the sensor sensitivity and detection capabilities;
- providing a lead optical fibre (single or multi moded) formed from a waveguide material which acts as an insensitive light guide between the sensing fibre and the sensing and locating system optics and optoelectronics interface;
- providing a lead optical fibre (single or multi moded) formed from a waveguide material which acts as an insensitive light guide between the sensing fibre and the excitation source;
- fusion splicing, or otherwise connecting, the sensor waveguide and the lead optical fibres so that cores of the waveguides are aligned and remain fixed at the splice;
- delivering the counter-propagating signals from the waveguide sensor, via the lead optical fibres, to an appropriate optical and electronic arrangement such that the time delay or difference between the signals may be measured and utilised to determine the location of the sensed event; and
- registering any changes in the waveguide sensor optical signals that may be utilised with a compatible sensing technique, such that the sensed parameter may be quantified and/or identified.

The preferred embodiment may also be said to reside in a method for producing a waveguide transmissive counter-propagating signal method and associated systems for locating events in optical waveguides, including, but not limited to, the steps of:

- Preparing an optical fibre (single or multi moded) formed from a waveguide material designed to simultaneously transmit counter-propagating optical signals.
- Preparing a sensor configuration (single or multi moded), with any appropriate waveguide length, any suitable geometry and compatible with the waveguide transmissive counter-propagating signal method and associated systems for locating events in optical waveguides, designed to optimise the sensor sensitivity and detection capabilities.
- Preparing a waveguide sensor and optical fibre lead by cleaving or polishing their ends so as to establish a flat, smooth surface. After taking necessary precautions to remove any contaminants from the cleaved or polished waveguide sensor and fibre lead end-faces, the waveguide sensor and fibre lead are placed end-to-end in a fusion splicing apparatus and fused together using the appropriate or desired fusion arc times and currents. The fusion splicing procedure may be repeated a number of times if necessary. The core and overall diameters of the waveguide sensor and fibre lead are not limited and translation stages or V-grooves may be used on the fusion splicing apparatus to centrally align the cores of the waveguide sensor and fibre lead before the fusion splicing procedure. Different combinations of waveguide sensor and fibre lead may require a different or unique set of fusion splicing parameters.
- Cleaving or polishing the waveguide sensor at any location after the fusion splice so as to establish a flat, smooth surface. The position of the cleave or polished surface establishes the localised length or sensing region of the sensor. After taking necessary precautions to remove any contaminants from the cleaved or polished waveguide sensor end-face, it is fusion spliced at a desired location to a second fibre lead.
- Preparing or connectorising the free ends of the fibre leads in any manner which facilitates attaching, connecting, splicing or coupling the fibre leads to the appropriate combination and arrangement of light source, couplers, photodetectors and signal processing electronics which achieves the transmissive counter-propagating signal method for locating events in optical waveguides.
- Preferably the manufactured sensor and/or the exposed fusion spliced region(s) may be protected by encapsulating or coating the desired region in a suitable device or material (ie. heatshrink fusion splice protector, acrylate, enamel, epoxy, polyimide, etc.).
- In a preferred embodiment the sensor waveguide is a multimode fibre and the lead fibres are singlemode fibres.
- In other embodiments a plurality of multimode fibres and singlemode fibres are fusion spliced in end-to-end relationship to form several sensitive and insensitive regions along the entire fibre assembly.
- In other embodiments a plurality of singlemode fibres are fusion spliced to respective multimode fibres and the plurality of singlemode fibres are connected to a coupler which in turn is connected to a further singlemode fibre to form a multiplexed sensor arrangement.
- In an alternate arrangement, the sensor fibre may be replaced by two or more suitably configured optical fibres (single or multi moded) and additional couplers may be utilised to connect the plurality of sensor fibres to the fibre optic leads. In this arrangement, a further number of couplers and photodetectors may be required at the instrumentation to facilitate the increased number of sensing and lead fibres.
- In a preferred embodiment of the above alternate arrangement the sensing part is formed by two suitably configured singlemode fibres and the insensitive leads are singlemode fibres. The two sensing fibres are connected to a lead fibre by the use of a singlemode coupler at either or both ends.

The present invention is effective on any optical waveguiding distributed sensing technique that may be arranged in a transmissive loop configuration. In a preferred embodiment, but without limitation, the distributed sensing technique is based on a modalmetric technique utilising the fusion

splicing of insensitive singlemode fibre to sensitive multimode fibre. [14,16] In yet another preferred embodiment, but without limitation, the distributed sensing technique is based on a Mach-Zehnder or Michelson interferometer utilising two singlemode fibres as the sensitive region.

Preferably the waveguide comprises at least one optical fibre and/or at least one optical fibre device. In some embodiments of the invention the waveguide may merely comprise an optical fibre without any additional elements. However, the optical fibre can include passive or active elements along its length. Furthermore, the optical fibre can include sensing elements along its length and those sensing elements can comprise devices which will respond to a change in the desired parameter in the environment of application and influence the properties and characteristics of the electromagnetic radiation propagating in the waveguide to thereby provide an indication of the change in the parameter.

Preferably any suitable CW or pulsed single-frequency or multiple wavelength source or plurality of sources may be employed. In a preferred embodiment, without limitation, a CW or pulsed coherent laser diode is utilised to supply the optical signal. In an alternate arrangement, multiple light sources, of the same or varying wavelengths, may be used to generate the counter-propagating signals.

The preferred embodiments of the present invention offer the potential to utilise all-fibre, low-cost optical devices in conjunction with laser diodes, light emitting diodes, photodetectors, couplers, isolators and filters.

Any suitable light source, coupler and photodetector arrangement may be used with the sensor and locating systems. In a preferred embodiment, the required optical properties of the light source are such that light may be launched into and propagated in the singlemode waveguide. For localisation, the light propagated in a singlemode fibre must remain singlemoded during the entire period of travel in the singlemode fibre. Once the light is launched into the multimode fibre from the singlemode fibre, several modes may be excited and the multimoded fibre will be sensitive to various parameters. Once the light is launched back into the singlemode fibre from the multimode fibre, only a single mode is supported and travels to the optical components of the system. Lead-in/lead-out fibre desensitisation and sensor localisation is achieved in this manner. In practical applications, the singlemode fibre should be made sufficiently long to attenuate all cladding modes in order to improve the signal-to-noise ratio. This preferred embodiment applies for both directions of travel of the transmissive counter-propagating optical signals.

Utilisation of properties and characteristics of the electromagnetic radiation propagating in the waveguide sensor enables monitoring to take place in a non-destructive manner. Thus, the sensor is not necessarily damaged, fractured or destroyed in order to monitor and locate the desired parameter.

In the method, according to the preferred embodiment of the invention, electromagnetic radiation is launched into an optical waveguide (single or multi moded), such as an optical fibre, from a light source, such as a pigtailed laser diode, fibre laser or light emitting diode, and propagates along the optical waveguide. The optical waveguide is connected (temporarily or permanently) to one arm of an optical waveguide light splitter or coupler and when the electromagnetic radiation reaches the light splitter the electromagnetic radiation can branch out into the two output waveguide arms of the light splitter. Each of the output arms of this light splitter are fusion spliced to other couplers, thus the optical radiation from the laser source is simultaneously launched into each of the other two couplers. These two couplers form the launch and detection ports for the dual-ended, counter-propagating method described above. The optical signal is simultaneously launched to the output waveguide arms of the couplers. Only one output arm is used in each coupler, the other is fractured or otherwise terminated to avoid back-reflections. The output arms of the couplers are either connected (temporarily or permanently) directly to the waveguide sensing element or to a lead optical waveguide which is connected (temporarily or permanently) to the waveguide sensing element. Any one of the output waveguide arms of the light splitter may be used to deliver the electromagnetic radiation to the sensor waveguide via an optical waveguide lead. Likewise, a

plurality of output waveguide arms may be used to deliver the electromagnetic radiation to a number of individual or multiplexed waveguide sensors. Each of the counter-propagating signals transmitted into the waveguide sensor propagates along the entire length of the waveguide until they reach the opposite ends and are launched back into the latter couplers in the opposite direction to the initial launch signals. The signals are each split in the reverse direction through the latter couplers. Part of the signals travel back towards the first coupler and laser, and the remainder of the signals travel along the unused arms of the latter couplers, which are terminated at photodetectors. The optical signals are simultaneously monitored by the two photodetectors. Appropriate electronics, signal processing schemes and algorithms process the signals from each detector and provide the location of the sensed event by determination of the time delay or difference between the signals effected by the same disturbance. The insensitive fibre optic leads may be very long to provide an additional time delay between the optical signals. This may assist engineering the technique into a practical working system.

In the method, according to an alternate preferred embodiment of the invention, the sensing section is formed by two or more suitably configured fibres (single or multi moded) and the insensitive leads are singlemode fibres. The plurality of sensing fibres are connected to the lead fibres by the use of additional singlemode couplers at either or both ends of the sensing fibres.

Preferably the instrument optical and electronic arrangements will utilise noise minimisation techniques.

Preferably, all the optical and electrical components will be located in a single instrument control box, with individual optical fibre input ports.

Electro-optic devices, acousto-optic devices, magneto-optic devices and/or integrated optical devices may also be utilised in the system.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will be further illustrated, by way of example, with reference to the following drawings in which:

Figure 1 is a view showing a general embodiment of the invention;

Figure 2 is a view showing an embodiment of the invention, utilising a modalmetric sensing technique;

Figure 3 is a view showing a further embodiment of the invention, utilising a Mach-Zehnder interferometric sensing technique;

Figure 4 shows an integrated fibre optic sensing and communication system, utilising a modalmetric sensing technique;

Figure 5 is a view showing yet a further embodiment of the invention;

Figure 6 is an oscilloscope plot illustrating the actual response of a system formed by the method of a preferred embodiment of the present invention, as detailed in Figure 5, when a perturbation acts on the fibre of a 14.71 km fibre link;

Figure 7 is another oscilloscope plot illustrating the actual response of a system formed by the method of a preferred embodiment of the present invention, as detailed in Figure 5, when a perturbation acts on the fibre of a 14.71 km fibre link; and

Figure 8 shows a combined fibre optic sensing and communication arrangement, utilising a modalmetric sensing technique and the ability to locate disturbances formed by the method of the preferred embodiments of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

With reference to Figure 1, a general set-up is illustrated where the distributed sensor 10 may be preceded and succeeded by certain arbitrary lengths of insensitive fibre leads 14a and 14b. It is important to emphasise that neither one or both of the insensitive fibre leads 14a and 14b are required for the methodology; they simply provide additional optical delay lines in order to add additional delay between the transmissive counter-propagating signals, to provide insensitive lead fibres and/or to facilitate specific placement of the sensing region(s). This may assist engineering the technique into a practical working system. The insensitive leads 14a and 14b may be fusion spliced 17, or otherwise connected, to the sensing fibre 10.

The optical fibre link (total distance d_x) is made up of an insensitive section 14a, of length d_a, fusion spliced 17 to a sensitive section 10, of length d_b, and finally fusion spliced 17 again to a third insensitive section 14b, of length d_c. The aim of the set-up is to locate a disturbance 18 (at point C) along the sensitive section of the fibre link 10 (between points B and D).

By injecting laser light into both points A and E simultaneously, the fibre link has two counter-propagating light beams. A perturbation 18 anywhere along the sensitive part of the fibre link 10 will cause two identical perturbation signals each to propagate in alternate directions, that is, from point C towards point E, and from point C towards point A. If the difference in time of arrival of each signal (respectively at points A and E) is known, then the point along d_b at which the disturbance occurred can be calculated using the following equations:

$$\begin{aligned} d_x &= d_a + d_b + d_c \\ &= d_a + d_{b1} + d_{b2} + d_c \end{aligned} \qquad (1)$$

The difference in time of arrival of each signal (respectively at points A and E), Δt, is given by:

$$\Delta t = (\Delta t_{b2} + \Delta t_c) - (\Delta t_{b1} + \Delta t_a) \qquad (2)$$

where Δt_a, Δt_{b1}, Δt_{b2} and Δt_c refer to the time taken for an optical signal to travel along d_a, d_{b1}, d_{b2}, and d_c , respectively, and can be calculated for known distances using $t = d/v$, where v is the speed of the optical signal in the fibre given by c/n_{fibre} , where c is the speed of light in a vacuum (3×10^8 m/s) and n_{fibre} is the effective refractive index of the optical fibre.

Rewriting the equation for Δt, we have:

$$\Delta t = \frac{d_{b2} + d_c - d_{b1} - d_a}{v} \qquad (3)$$

Using the equation for d_x, we can substitute $d_{b2} = d_x - d_a - d_c - d_{b1}$, giving:

$$\begin{aligned} \Delta t &= \frac{d_x - d_a - d_c - d_{b1} + d_c - d_{b1} - d_a}{v} \\ &= \frac{d_x - 2d_a - 2d_{b1}}{v} \\ &= \frac{d_x - 2(d_a + d_{b1})}{v} \end{aligned} \qquad (4)$$

Therefore, the location of the disturbance referenced from point A is given by:

$$Point\quad of\quad disturbance_A = (d_a + d_{b1}) = \frac{d_x - (v\Delta t)}{2} \tag{5}$$

Similarly, the location of the disturbance referenced from point E is given by:

$$Point\quad of\quad disturbance_E = (d_c + d_{b2}) = \frac{d_x + v\Delta t}{2} \tag{6}$$

It is interesting to note that this result illustrates that it is required to only know the length of the entire fibre link, d_x, and not the respective lengths of the various sensitive and insensitive fibre regions in the system. This information can be easily obtained at the design and installation stages of a project, or post-installation by the use of an OTDR. Then, once the total length is known and the time delay, Δt, is measured by the system, it is a straight forward calculation using Equations 5 or 6 to determine the location of the sensed event.

In the embodiment of Figure 2, CW coherent laser light is launched into a singlemode optical fibre 15, from a pigtailed laser diode 20 and fibre isolator 22, and propagates along the optical fibre 15. The optical fibre 15 is fusion spliced 41 to one arm of a singlemode fibre optic coupler 24 and when the light reaches the coupler 24 the light can branch out into the two output arms of the coupler 24. Each of the output arms of this coupler 24 are fusion spliced 42a and 42b to other singlemode fibre couplers 26a and 26b, respectively, thus the light from the laser source 20 is simultaneously launched into each of the other two couplers 26a and 26b. These two couplers 26a and 26b form the launch and detection ports for the dual-ended, counter-propagating method utilising a modalmetric sensing technique. The optical signal is simultaneously launched to the output arms 27a and 27b of the couplers 26a and 26b. Only one output arm 27a and 27b from each coupler 26a and 26b, respectively, is used, all other unused arms of couplers are fractured or otherwise terminated to avoid back-reflections 19. The output arms 27a and 27b of the couplers 26a and 26b are terminated at singlemode fibre optic bulkhead connectors (through adaptors) 28a and 28b. A connectorised singlemode fibre lead 14a is connected to the through adaptor 28a, such that the light from coupler 26a is launched into the fibre link in one direction. Similarly for the counter-propagating signal, a connectorised singlemode fibre lead 14b is connected to the through adaptor 28b, such that the light from coupler 26b is launched into the fibre link in the opposite direction. The singlemode fibre lead 14a is fusion spliced 43 to one end of the multimode sensing fibre 10 and the singlemode fibre lead 14b is fusion spliced 44 to the opposite end of the multimode sensing fibre 10, thus forming the transmissive counter-propagating sensing loop configuration required. Each of the counter-propagating signals transmitted through the fibre sensor 10 propagates along the entire length of the fibre link until they reach the opposite ends and are launched back through leads 14a and 14b and bulkhead through adaptors 28a and 28b into the couplers 26a and 26b, respectively, in the opposite direction to the initial launch signals. The signals are each split in the reverse direction through couplers 26a and 26b. Part of the signals travel back towards the first coupler 24 and laser 20, and the remainder of the signals travel along the arms 16a and 16b of the latter couplers 26a and 26b, respectively, which are terminated at photodetectors 30a and 30b. The fibre isolator 22 is used to reduce the amount of light launched back into the laser diode. The optical signals are simultaneously monitored by the two photodetectors 30a and 30b. Appropriate electronics, signal processing schemes and algorithms process the signals from each detector 30a and 30b and provide the location 18 of the sensed event by determination of the time delay or difference between the signals effected by the same disturbance. The insensitive fibre optic leads 14a and 14b may be very long to provide an additional time delay between the optical signals, if required.

In the embodiment of Figure 3, CW coherent laser light is launched into a singlemode optical fibre 15, from a pigtailed laser diode 20 and fibre isolator 22, and propagates along the optical fibre 15. The optical fibre 15 is fusion spliced 41 to one arm of a singlemode fibre optic coupler 24 and when

the light reaches the coupler 24 the light can branch out into the two output arms of the coupler 24. Each of the output arms of this coupler 24 are fusion spliced 42a and 42b to other singlemode fibre couplers 26a and 26b, respectively, thus the light from the laser source 20 is simultaneously launched into each of the other two couplers 26a and 26b. These two couplers 26a and 26b form the launch and detection ports for the dual-ended, counter-propagating method utilising a Mach-Zehnder interferometric sensing technique. The optical signal is simultaneously launched to the output arms 27a, 27c and 27b of the couplers 26a and 26b. Only one output arm 27b from coupler 26b, is used, all other unused arms of couplers are fractured or otherwise terminated to avoid back-reflections 19. The output arms 27a, 27c and 27b of the couplers 26a and 26b are terminated at singlemode fibre optic bulkhead connectors (through adaptors) 28a, 28c and 28b. Connectorised singlemode sensing fibres 10a and 10c are connected to the through adaptors 28a and 28c, respectively, such that the light from coupler 26a is simultaneously launched into the fibre link in one direction. Alternately, a further coupler could be used with arms 10a and 10c to replace using arm 27c and adaptor 28c. Similarly for the counter-propagating signal, a connectorised singlemode fibre lead 14 is connected to the through adaptor 28b, such that the light from coupler 26b is launched into the fibre link in the opposite direction. The singlemode sensing fibres 10a and 10c are fusion spliced 45 and 46, respectively, to one end of a singlemode coupler 60 and the singlemode fibre lead 14 is fusion spliced 47 to one arm of the coupler 60 on the opposite side, thus forming the transmissive counter-propagating sensing loop configuration required. The unused arm of coupler 60 is fractured or otherwise terminated to avoid back-reflections 19. Each of the counter-propagating signals transmitted through the fibre arrangement propagates along the entire length of the fibre link until they reach the opposite ends and are launched back through bulkhead through adaptors 28a, 28c and 28b into the couplers 26a and 26b, respectively, in the opposite direction to the initial launch signals. The signals are each split in the reverse direction through couplers 26a and 26b. Part of the signals travel back towards the first coupler 24 and laser 20, and the remainder of the signals travel along the arms 16a and 16b of the latter couplers 26a and 26b, respectively, which are terminated at photodetectors 30a and 30b. The fibre isolator 22 is used to reduce the amount of light launched back into the laser diode. The optical signals are simultaneously monitored by the two photodetectors 30a and 30b. Appropriate electronics, signal processing schemes and algorithms process the signals from each detector 30a and 30b and provide the location 18 of the sensed event by determination of the time delay or difference between the signals effected by the same disturbance. The insensitive fibre optic lead 14 may be very long to provide an additional time delay between the optical signals, if required.

Figure 4 illustrates an integrated fibre optic sensing and communication system, utilising a modalmetric sensing technique, and is described in detail in the example further below.

Figure 5 illustrates a view of an embodiment of the invention used to verify the feasibility of the invention, and is described in detail in the example further below.

Figure 6 illustrates an oscilloscope plot illustrating the actual response of a system formed by the method of a preferred embodiment of the present invention, as detailed in Figure 5 and the example further below, when a perturbation acts on the fibre of a 14.71 km fibre link.

Figure 7 illustrates another oscilloscope plot illustrating the actual response of a system formed by the method of a preferred embodiment of the present invention, as detailed in Figure 5 and the example further below, when a perturbation acts on the fibre of a 14.71 km fibre link.

Figure 8 illustrates a combined fibre optic sensing and communication arrangement, utilising a modalmetric sensing technique and the ability to locate disturbances formed by the method of the preferred embodiments of the present invention. In a practical application of this technique, it will usually be desirable for both launch points of the counter-propagating signals to be at the same physical location. This is easily achieved by using a multi-fibre cable which will effectively form a single-ended system. In this arrangement, one singlemode fibre is utilised as the communications fibre, whilst three fibres, two singlemode and one multimode, are required to set-up the modalmetric intrusion sensor (event detection and location determination) over the specified region of interest (shaded area). A perturbation anywhere along the multimode fibre in the shaded region,

will generate two counter-propagating perturbation signals. Measuring the time difference in their respective time of arrival at the transmitter end of the link will allow the location of the disturbance to be determined.

EXAMPLES OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the present invention have been tested illustrated by the following example. The optical fibre transmissive counter-propagating signal method and associated system was constructed in order to demonstrate the feasibility of producing the invention described herein. Not all of the results obtained to date are detailed in the following example.

Example: Location of Point of Disturbance Using the Modalmetric Effect:

It has long been known that when a multimode optical fibre is disturbed, the distribution of the modes is affected. This modulation of the modal distribution in a multimode fibre is known as the modalmetric effect. The modalmetric effect in a multimode fibre can be used to sense and monitor vibrations, disturbances or movement of the fibre itself, or any structure or object the fibre is attached to, by detecting an intensity change in the speckle pattern output of the fibre. Modalmetric sensors can therefore be used as vibration sensors in structural monitoring, condition monitoring of high voltage equipment, intrusion detection of cables or pipelines, and in fence perimeter security. [14-16]

Initially, optical fibres were deployed mainly in long haul and high speed telecommunication systems. However, with the decrease in cost of optical fibre cable, and optoelectronic sources and detectors, optical fibres are now being used as the main carrier in many other communications applications such as, LAN/WAN backbones, and in the private communications networks of many small and large organisations (ie., banks, defence, government, public utilities and multinationals). Many of these communications networks involve the transfer of sensitive information which has made the security of the communications link a high priority.

The modalmetric effect can easily and effectively be employed to guard against any intrusion into or tampering with an optical fibre cable. A typical set-up where the sensing is integrated into a fibre communications system is shown in Figure 4. [16]

Both the sensing system 100a and 100b and the communication system 200a and 200b are integrated into the same optical fibre 10. The wavelength of the sensing system is chosen so as not to interfere with the communications signal (via wavelength multiplexing) and also such that the fibre link is multimoded for the sensing wavelength. Several other configurations are possible, however, they all work on the same principle. The modalmetric processing unit will detect any perturbation at any point along the fibre link.

Up until now, the modalmetric sensing effect has only had the capability of sensing disturbances along a distributed multimode optical fibre sensing length, without being able to locate the exact point of the disturbance. Recent experiments by the inventors have shown that it is now possible to locate the disturbance by determining the time delay between two counter propagating signals, according to the method of the invention described herein. The experimental work is described below for the arrangement illustrated in Figure 5.

The set-up described in Figure 5 is similar to that in Figure 1, with the difference that there are now two counter-propagating light signals in the fibre link. Again, the sensing fibre may be a dedicated fibre in the fibre cable, or the same fibre as the communications fibre. If a perturbation is applied to the multimode fibre at the point indicated (point A), two similar or identical time varying optical signals will be generated consistent with the modalmetric effect, each travelling in the opposite direction. The perturbation signal consistent with Input 1 (PS1) will arrive at Port 2 (Output 1) before the perturbation signal consistent with Input 2 (PS2) arrives at Port 1 (Output 2). This is due to the fact that PS2 needs to propagate through 14.71 km more optical fibre than PS1. By measuring the time delay between the two perturbation signals, the location of the disturbance can

be calculated. In the above set-up, assuming a refractive index for the fibre of 1.457, then the time difference between the two signals can be calculated as:

$$\Delta t = \frac{14.71x10^3 m}{(3x10^8 m/s)/(1.457)} = 71.49\mu s. \qquad (7)$$

Several measurements were performed on a transmissive counter-propagating fibre loop arrangement described in Figure 5. An experimental set-up the same as that detailed in Figure 2 was used to measure the perturbation signals and a Hewlett Packard 54810A Infinium digitising oscilloscope was used to sample the perturbation signals and manually measure the resultant time difference. Figures 7 and 8 illustrate results from two such captures. As can be seen from both captures, there is clearly a delay between the two perturbation signals, which has been measured as 65 μs and 70 μs respectively, comparing well with the theoretical calculation of 71.5 μs. The error (effectively 300 m) may be a result of the assumption of the value of the effective refractive index of the fibres and by the inaccuracy in the manual measurement of the time delay. These errors could be reduced by knowing the actual effective refractive index of the fibre and by employing digital signal processing means to accurately determine the time delay.

APPLICATIONS OF THE PREFERRED EMBODIMENTS

Optical devices and systems made by the method of the invention are useful in a wide variety of applications and fields. Not inclusive, but indicatively, the following examples illustrate some potential users of the fibre optic sensing and locating methods described herein:

- Road, rail, dam and bridge maintenance firms.
- Owners, operators and insurers of infrastructure.
- Pipeline construction companies, contractors and operators.
- Petroleum and petrochemical companies.
- Offshore oil rig operators and maintenance firms.
- Perimeter fence or wall security firms
- Security firms.
- Government and military organisations.
- Power generation and distribution industry
- Power, water and fuel facilities.
- Tower owners and operators.
- Aircraft manufacturers, repairers and operators.
- Non-destructive evaluation firms and equipment manufacturers.
- R&D companies and laboratories.
- Instrument and sensor manufacturers.
- Sports equipment and facilities manufacturers and operators.
- Mine operators.
- Owners, operators and insurers of marine vessels.
- Quality Assurance and safety firms.
- Building management firms.
- Industrial equipment operators and manufacturers.
- Nuclear power plant manufacturers, owners and operators.
- Telecommunications firms or operators.
- Any application requiring the detection, measurement and location of a disturbance to an optical fibre cable.

The claimed invention overcomes the disadvantages and limitations of many existing fibre optic distributed sensing techniques. Furthermore, it is capable of detecting and locating dynamic and transient events and it is less complex and lower cost than most other fibre optic distributed sensors capable of locating disturbances. Such a system would offer lower cost and increased operational and safety advantages over existing technologies and has the potential for short to long term installation monitoring in plant and ecological environments.

Since modifications within the spirit and scope of the invention may readily be effected by persons skilled within the art, it is to be understood that this invention is not limited to the particular embodiments described by way of example hereinabove.

FUTURE FIBRE TECHNOLOGIES PTY. LTD.

By EDWARD TAPANES, Director of FFT Pty. Ltd. — 18 December 1998
(Name of Applicant) — (Date)
(BLOCK LETTERS)

Figure 1

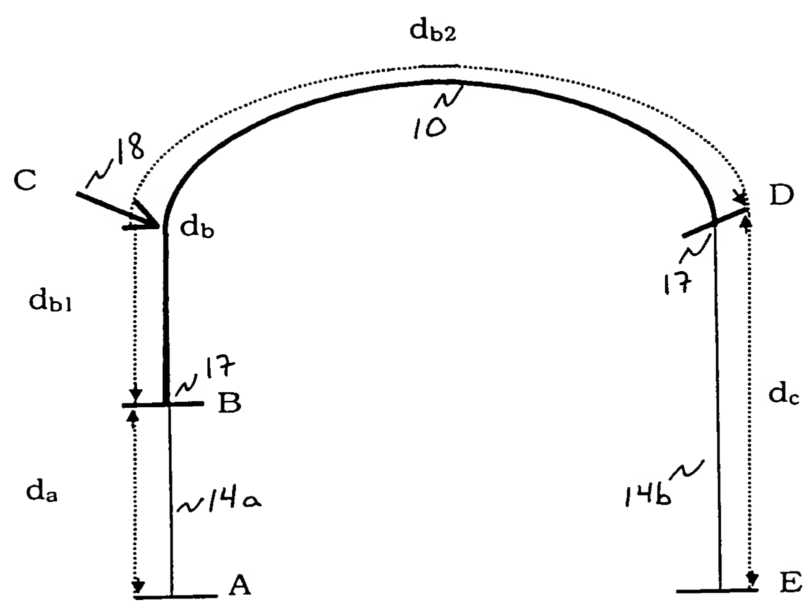

Figure 2

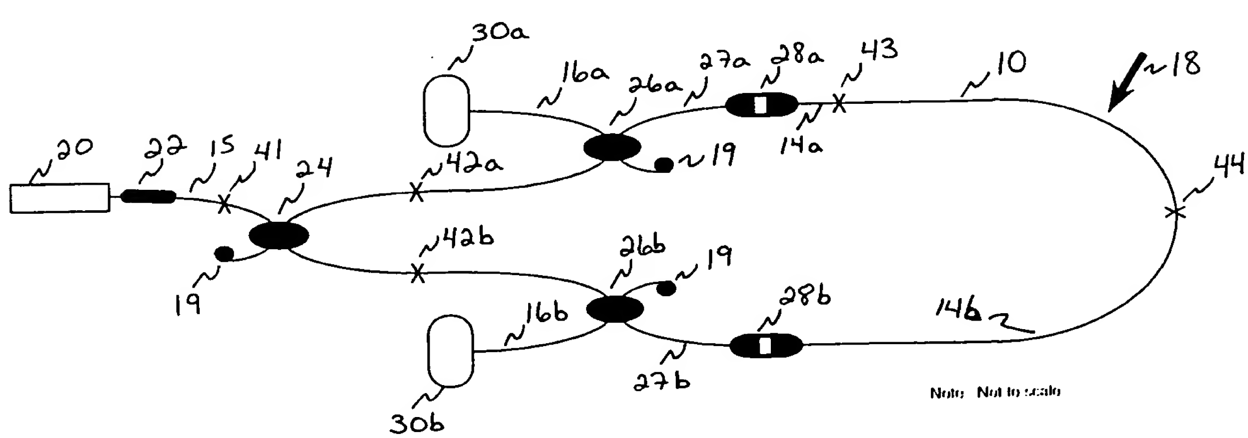

Figure 3

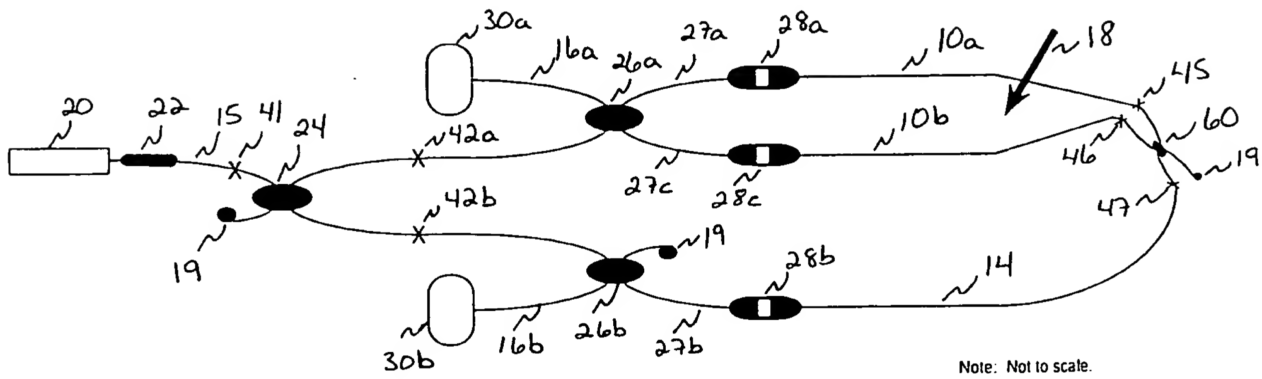

Figure 4

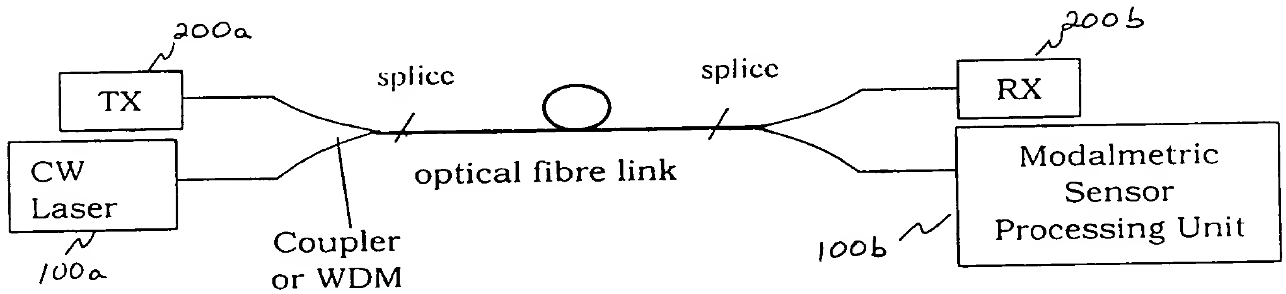

Figure 5

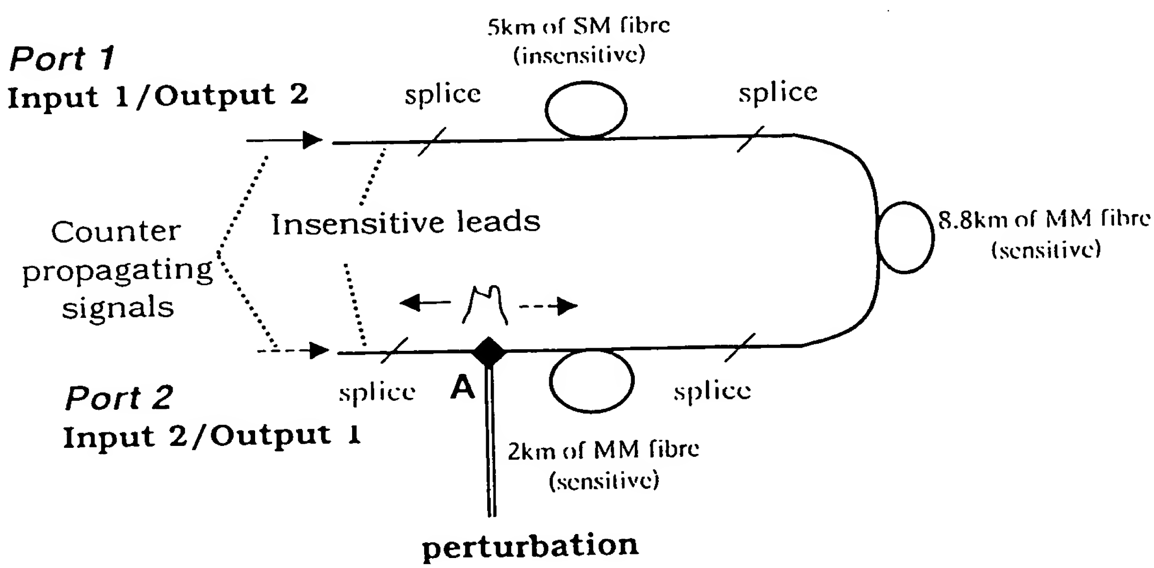

Figure 6

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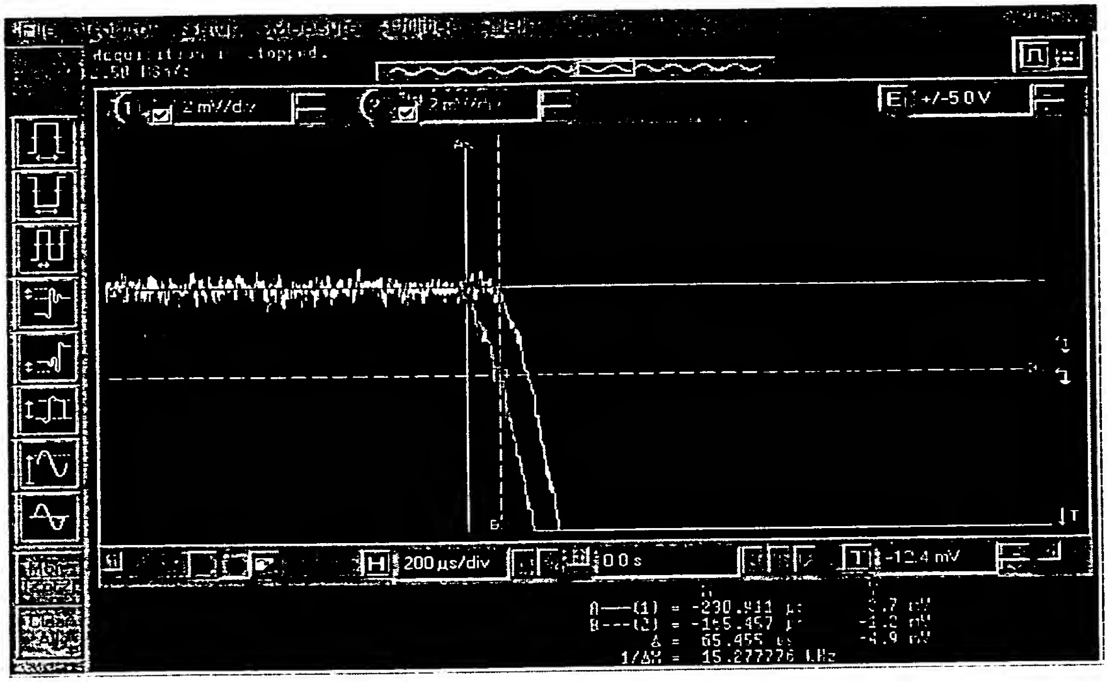

Figure 7

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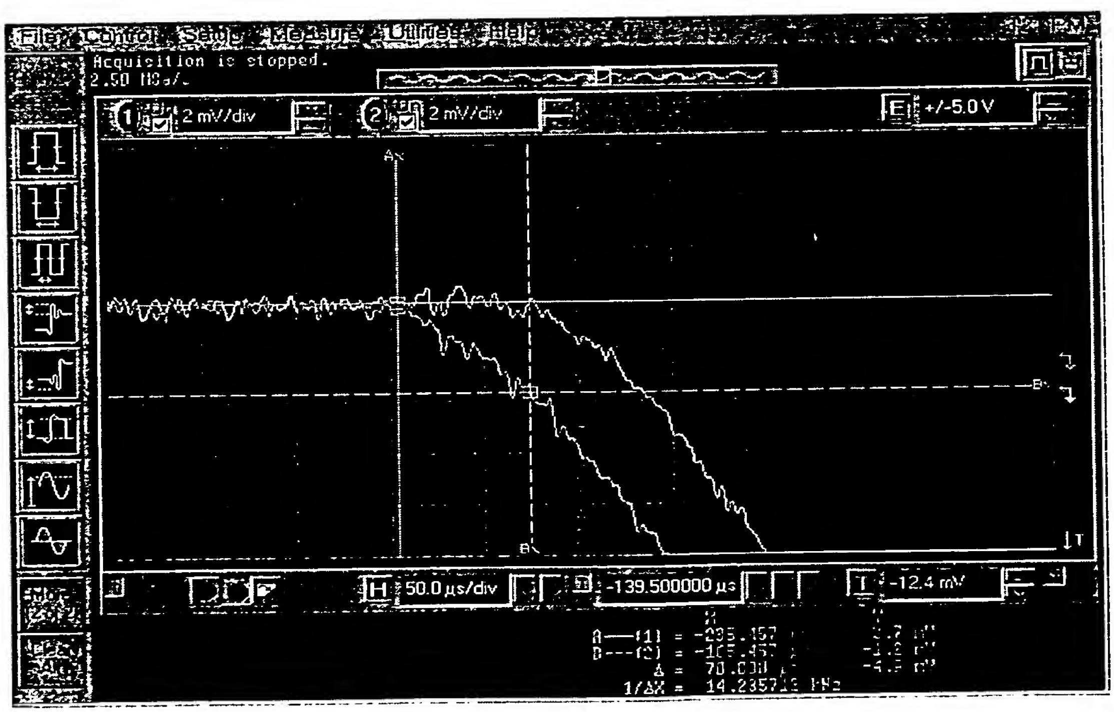
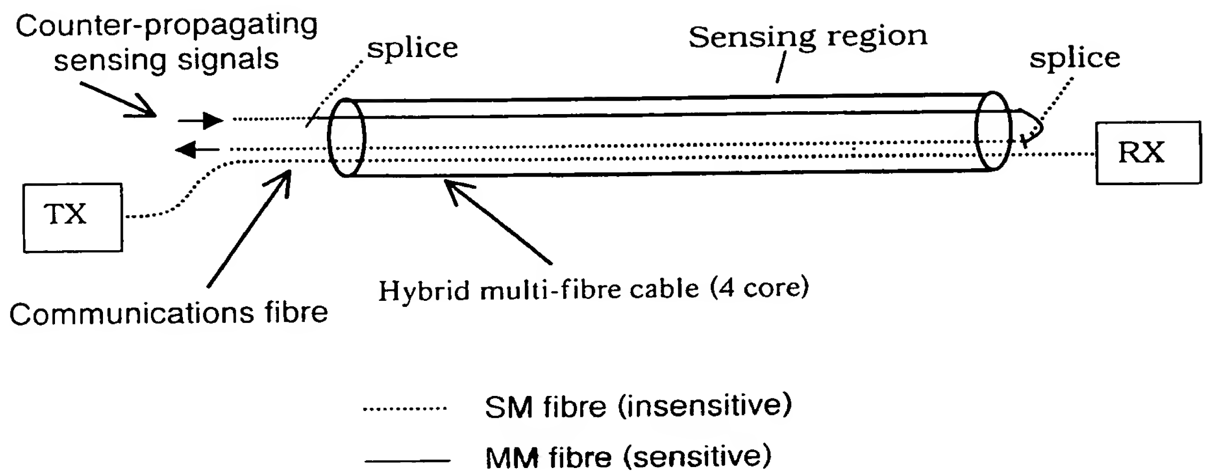


Figure 8


Counter-propagating sensing signals
splice
Sensing region
splice
TX
RX
Communications fibre
Hybrid multi-fibre cable (4 core)
SM fibre (insensitive)
MM fibre (sensitive)

PCT/AU99/01028 #3

09/857340

REC'D 05 JAN 2000

Patent Office
Canberra

I, KIM MARSHALL, MANAGER PATENT OPERATIONS hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. PQ 0126 for a patent by FUTURE FIBRE TECHNOLOGIES PTY. LTD. Filed on 03 May 1999.

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WITNESS my hand this
Twenty-second day of December 1999

KIM MARSHALL
MANAGER PATENT OPERATIONS

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AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

Invention Title Intrinsic Securing of Fibre Optic Communication Links

The invention is described in the following statement:

INTRINSIC SECURING OF FIBRE OPTIC COMMUNICATION LINKS

FIELD OF THE INVENTION

This invention relates to optical waveguide systems formed for securing live-fibres against tampering and tapping-off of data in optical fibre communication links.

ART BACKGROUND

Optical devices are commonly used in industry and science and include laser cavities, waveguides, lenses, filters and other optical elements and their combinations. Such optical devices are used in a variety of instruments and installations.

Photonics technology has revolutionised the communications and sensor fields. This is mainly due to the rapid development of optical and opto-electronic devices. A wide variety of glass materials, material-dopants and waveguide structures are available and this provisional specification relates to optical waveguide systems formed for securing live-fibres against tampering and tapping-off of data in optical fibre communication links.

Communications using an optical fibre have a number of attractive features and advantages over conventional communication means. These advantages include the following:

- Greater bandwidth and capacity
- Electrical isolation
- Low error rate
- Immunity to external influences
- Immunity to interference and crosstalk
- Signal security
- Ruggedness and flexibility
- Potential low cost

The high expectations of optical fibres as information carriers in communication systems have been justified by their performance over the past two decades. Due to their high bandwidth, low attenuation and mechanical properties, each fibre is capable of replacing over 1000 copper wires in telecommunication systems. With these characteristics it is no surprise that optical fibres have become the most affordable and efficient medium available in the field of telecommunications. Furthermore, the increased capacity, ease of system expandability, and reduced installation, operation and maintenance costs of the technology, is also making a strong impact in industry, replacing many of the traditional communication systems.

The use of optical fibres as the main backbone of most communication systems has meant that large amounts of information can be efficiently and cost effectively transferred from point to point. Modern fibre optic communications networks deploy optical fibre over millions of kilometres worldwide, carrying important and confidential information of a government, military, financial and personal nature. Although it was initially thought that optical fibre transmission would be inherently secure, we now know that it is relatively easy to 'tap' information out of an optical fibre with negligible interference to the optical signal. It has became obvious that in order to extract 100% of the information which is transmitted via the fibre optic cable, it is sufficient to bend the fibre only slightly or clamp onto it at any point along its length and photons of light will leak into the receiver of the intruder. Even when only 0.1 dB (2%) of the signal is leaking, it will contain all of the information being transmitted in each photon. The user at the other end will never know that his information has been tampered with since they will experience no apparent interference with their communications. A loss of 0.1 dB represents the lowest practical detectable optical loss in a fibre system by modern test equipment and network management systems. The same

technique could also be used in order to introduce false information or to corrupt existing information flow.

This can have serious security implications for users of optical fibre communication systems, especially telecommunications carriers, banks, brokerage houses, treasuries, defence organisations, government organisations, embassies and corporations, to name a few. All these information carriers and users are totally vulnerable to intrusion, tampering and tapping-off of their data. This vulnerability issue has not been publicly raised to-date because suppliers and users have failed to understand the potential threat and because there have been no effective solutions. Most people today still believe that optical fibres are the most secure means of communications, which is not actually true.

Until recently, the only available techniques of protection against intrusion of fibre optic telecommunications involved the use of:

- encryption of the information being transmitted;
- physical security systems based on physical barriers (ie., thicker coatings on the fibres, thicker and harder protective jackets on the cables and housing the cables in conduits); and
- static or slowly varying measurements using optical time domain reflectometers (OTDRs) to detect fibre fracture, sharp bends, fibre attenuation or connector losses.

Encryption techniques can be very costly, they often slow the system speed considerably/unacceptably and are not ever totally secure.

Physical security measures are not truly effective in uncovering tampering with a fibre optic communications link since they require the fibre to be cut, fractured or severely bent before the problem can be detected.

OTDRs are ineffective at detecting dynamic or transient disturbances to a fibre cable. In addition, their functionality limits them to measuring only optical losses, but with relatively low sensitivity, thus they are practically limited to detecting significant and permanent or very slowly changing (and often destructive) effects on the cable.

With millions of kilometres of optical fibre deployed worldwide, the monitoring of fibre cable tampering, integrity and the prediction of the onset of failure and damage is critical to the security and reliability of fibre communication systems. Most current techniques for monitoring fibre optic cable tampering or integrity are based on static or very-slowly varying measurements using an OTDR. However, it would be a technological breakthrough to be able to obtain real-time, quasi-static and dynamic information about non-destructive disturbances anywhere along the fibre cable. This would have the further advantage of monitoring any disturbance to the cable and any structure or material near the cable or to which the cable is attached. Such a capability should also enable simultaneous, real-time fibre optic communications and sensing applications such as structural integrity monitoring, leak detection, ground monitoring, machine condition monitoring and intrusion detection.

This is possible because optical fibres can be more than mere signal carriers. Light that is launched into and confined to the fibre core propagates along the length of the fibre unperturbed unless acted upon by an external influence. Specialised sensing instrumentation may be configured such that any disturbance of the fibre which alters some of the characteristics of the guided light (ie., amplitude, phase, wavelength, polarisation, modal distribution and time-of-flight) can be monitored, and related to the magnitude of the disturbing influence. Such modulation of the light makes possible the measurement of a wide range of events and conditions, including:

- Strain/residual strain
- displacement
- damage
- cracking
- vibration/frequency

- deformation
- impact
- acoustic emission
- liquid levels
- pressure
- temperature
- load

Fibre optic sensor technology has progressed at a rapid pace over the last decade. Different configurations of fibre sensing devices have been developed for monitoring specific parameters, each differing by the principle of light modulation. [1] Fibre optic sensors may be intrinsic or extrinsic, depending on whether the fibre is the sensing element or the information carrier, respectively. They are designated "point" sensors when the sensing gauge length is localised to discrete regions. If the sensor is capable of sensing a measurand field continuously over its entire length, it is known as a "distributed" sensor; "quasi-distributed" sensors utilise point sensors at various locations along the fibre length. Fibre optic sensors can be transmissive or can be used in a reflective configuration by mirroring the fibre end-face.

Hence, fibre optic sensors are actually a class of sensing device. They are not limited to a single configuration and operation unlike many conventional sensors such as electrical strain gauges and piezoelectric transducers. Consequently, fibres are now replacing the role of conventional electrical devices in sensing applications to the extent where we are now seeing a multitude of sensing techniques and applications being explored for practical gain.

However, to-date most fibre optic sensor systems are based on point sensing devices, thus requiring a large number of sensors to cover a large area or long length of interest. The subsequent cost and complexity of such systems is most often restrictive or impractical.

Very few distributed techniques have been developed and are commercially available. [2,3] Of those that have been developed, most monitor only temperature and fewer still have the capability to actually locate the region or position of the sensed parameter or disturbance along the fibre length; they simply detect, alert and sometimes quantify that an event has occurred. Furthermore, many of these techniques are often limited to monitoring static or very slowly varying parameters due to the requirement of measuring and averaging the time-of-flight of very narrow, low power back-reflected optical pulses (most are based on OTDR principles).

However, it would be a significant advance to be able to also obtain real-time, quasi-static and dynamic information about any form of disturbance to the optical fibre and their location, particularly transient events which are too quickly occurring to detect with OTDR techniques. This can be achieved by combining a distributed sensing technique incapable of locating the events with a compatible technique that is capable of locating the events. Such a capability would enable truly distributed sensing applications such as fibre cable tampering or third-party interference detection, as well as offering the further advantage of monitoring any structure or material near the fibre or to which the fibre is attached (ie., structural integrity monitoring, pipeline leak detection, ground monitoring, machine condition monitoring and intrusion detection of high security areas).

In 1995, the author of this provisional specification published a PCT Patent for a novel fibre optic distributed vibration sensing technology. [4] The sensing technique was based on a unique fibre optic modalmetric sensor configuration. This technology overcomes the inherent weaknesses of most multimode fibre optic sensors, offering truly localised, mechanically stable and linear sensing. The sensing is achieved by using a modalmetric interference effect, which is based on the modulation of the modal distribution (effectively changing the intensity) in a multimode optical fibre by external perturbations. In this method, the sensor response is a direct function of the

disturbance on the sensitive portion of the fibre. The disturbance may be in the form of physical movement (ie., compression (radially or axially), elongation, twisting, vibration, etc.) or microphonic effects (ie., travelling stress waves or acoustic emissions). The ability to vary the sensing length to fit specific applications is a major and unique advantage of this technology. This is particularly relevant if long sensing lengths are required, as is the case when combining the sensing technique with fibre optic communications. The only limitation imposed on the sensing length is in the optical power budget of the system. Therefore, if a longer sensing length is desired a higher power laser is required.

The Tapanes fibre optic distributed vibration sensor provides a simple, effective and inexpensive technique to detect and characterise both small and large disturbances on any optical fibre cable, anywhere along its entire length, and in real-time. This offers the capability of simultaneously utilising a fibre optic communications cable as a tampering-alert, intrusion-alert or integrity-testing sensing cable, thus providing continuous, real-time monitoring of the fibre cable and any structure near the cable (ie., ground, tunnels, ducts, pipes, buildings, equipment, vessels, etc.).

One of the key features of the technology is its configuration-flexibility since it is wavelength independent. This makes it possible to use with any type of optical fibre, thus it can be simultaneously retrofitted and integrated into any existing fibre optic communications cable, without requiring the installation and cost of a new cable.

Subsequently, this technology was demonstrated by Tapanes et. al. to be capable to be operated simultaneously with a communications system within the same optical fibre or cable [5], adding significant value to any communications system in regard to security and enabling easy integration of the distributed sensing technology into an existing fibre optic network. To achieve this, they demonstrated a wavelength multiplexed optical fibre system which can be used in both standard singlemode (9/125 μm) and standard multimode (62.5/125 μm) optical fibre systems for simultaneous communications and sensing.

Figure (1) illustrates the configuration used for the demonstration of a simultaneous fibre optic communications and sensing system. The system configuration consisted of the fibre link, either single or multi moded, with standard 3 dB (50% splitting ratio), 2x2 fibre couplers at each end to allow for the multiplexing and demultiplexing of the two wavelengths at the transmitter and receiver ends, respectively. The choice of sensing wavelength was important as the responsivity of the InGaAs detector in the communication channel needed to be negligible at the sensing wavelength. Thus, the communication channel was chosen to operate at a wavelength of 1300 nm whilst the sensing channel was chosen to operate at either 633 nm or 850 nm. This ensured that inter-channel crosstalk was negligible, as the Si detector utilised in the sensing channel would not respond to the 1300 nm communications signal.

Figure (2) illustrates the results from the sensing arrangement shown in **Figure (1)** when a vibrational disturbance was applied to a short section of the fibre link. A vibrational disturbance was applied to a small section (5 cm) of the fibre link using a cantilever beam arrangement. The fibre was simply taped longitudinally along the beam length. A typical sensing response is shown in **Figure (2)** for a 28 km singlemode (SM) link and a 53 km multimode (MM) fibre link. As can be seen, very good signal quality was obtained. In addition, the Fast Fourier Transforms (FFTs) clearly identify the natural frequency of the beam to be ~18 Hz with both links.

Simultaneous, non-interfering communication and sensing was thus successfully demonstrated on a SM optical fibre link with a communications data rate of 50 Mb/s as well as a 500MHz analog communications channel bandwidth system using a sensing wavelength of 633 nm and 850 nm, respectively.

While this technology had proven itself effective for securing fibre optic communications cables it still had one significant limitation that would limit its commercial attractiveness; it was not

capable of pin-pointing the location of the disturbance to the fibre. In order to overcome this major limitation, in 1998 Tapanes et. al. developed and demonstrated a compatible methodology and technology for locating disturbances in fibre optic sensing systems. [6] The technique relies on the measurement of the time delay or difference between transmissive counter-propagating optical signals affected by the same event in a two-ended fibre arrangement. In this novel arrangement, as illustrated in **Figure (3)**, continuous-wave (CW) optical signals are simultaneously launched, preferably from a single light source, into opposite ends of a sensing optical fibre or set of fibres and simultaneously detected by synchronised photodetectors. Pulsing of the optical signal is not necessary, although it may be employed in some arrangements. Any sensed parameter which acts to alter the counter-propagating signals will effect both signals in the same manner, but because the effected counter-propagating signals must each continue travelling the remainder of the fibre length to their respective photodetectors there is a resultant time delay or time difference between the detected signals. The time delay is directly proportional to the location of the sensed event along the fibre length. Therefore, if the time delay or difference is detected and measured, the location of the event can be determined. At the same time, if a compatible sensing mechanism is being employed the sensed event can be quantified and/or identified (ie., strain, vibration, acoustic emission, temperature transients, etc.). In addition, non-sensitive fibre optic delay lines may be connected to the sensing fibre at either or both ends in order to add additional delay between the transmissive counter-propagating signals and to provide insensitive lead fibres.

This technique enables dynamic and transient events to be located in virtually any distributed fibre optic sensing system, and its transmissive counter-propagating technique does not possess the limitations and complexities of OTDR principles.

The four main innovative features of the invention are:

- Operates on virtually any existing type of transmissive distributed fibre optic sensor, enabling dynamic and transient events to be detected, quantified, characterised and located anywhere along the length of the optical fibre.
- Operates in a transmissive configuration, thus delivering the entire optical signal and power back to the detector and not requiring signal averaging.
- Determines the location of events via the time delay measured between counter-propagating optical signals effected by the same disturbance. The spatial resolution is, therefore, limited and set by the speed of the data acquisition system.
- Does not require laser pulsing, although it is capable of operating with pulsed techniques.

With the two above-mentioned advances [4,6], Tapanes et. al. [6] proposed one possible configuration for monitoring and locating disturbances to a fibre optic communications cable by utilising a non-active ("dark") fibre in the cable, as illustrated in **Figure (4)**. However, feedback from industry has also emphasised the desire to monitor active ("live") fibres in certain circumstances.

A simple solution to this requirement would be to utilise the wavelength multiplexing method illustrated in **Figure (1)**. However, the use of 3 dB couplers imposes an additional minimum optical loss of 6 dB, which could severely impact the optical power budget of most communications systems. Ultimately, it would be desirable to implement the modalmetric sensing and the locating techniques in such an optical arrangement that would minimise the optical power losses to a communications system. If, likewise, the arrangement also minimised the optical power losses to the sensing system, then it would be possible to design and configure a communications node or junction by-pass arrangement for the sensing signal in order to extend the

sensing fibre length beyond one communication node. This would be particularly useful for ring topology networks.

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BRIEF SUMMARY OF THE INVENTION

The object of the present invention is to provide optical waveguide systems formed for securing live-fibres against tampering and tapping-off of data in optical fibre communication links, while minimising optical power losses to both the communications and sensing signals.

The present invention relies on the utilisation of wavelength multiplexing/demultiplexing (WDM) waveguide devices to combine and separate the individual wavelength components of the communications and sensing signals in the same optical fibre, while minimising the optical power losses. For example, while a typical 2x2 coupler splits the transmitted light in either direction into two roughly-equal signals (50/50% power split), a WDM coupler is specifically designed to efficiently tap-off or insert specific wavelengths with considerably less loss (typically ~10%). Therefore, it is now possible to design some specific optical waveguide arrangements that can provide security for live-fibres against tampering and tapping-off of data in optical fibre communication links, while minimising optical power losses to both the communications and sensing signals.

The objects, advantages and other features of the present invention will become more apparent upon reading of the following non-restricted descriptions of preferred embodiments thereof, given for the purpose of examplification only with reference to the accompanying drawings.

The preferred embodiment of the present invention provides a waveguide system for securing live-fibres against tampering and tapping-off of data in optical fibre communication links, which may include:

- providing a sensing system light source operating at a wavelength different to the communications system light source;
- providing a wavelength multiplexing waveguide light splitter or coupler (single or multi moded) which efficiently combines the sensing and communications signals into one waveguide;
- providing a silica waveguide (single or multi moded) for receiving light from the wavelength multiplexing waveguide light splitter or coupler, the silica waveguide being capable of transmitting the sensing and communications signals in the required manner along its length, but particularly such that the sensing wavelength and the waveguide characteristics satisfy the

requirements of the modalmetric sensing [4] and locating [6] techniques described earlier while unaffecting the communications signal;

- providing a wavelength demultiplexing waveguide light splitter or coupler (single or multi moded) which efficiently splits or separates the sensing and communications signals into two output waveguide ports while minimising optical power losses to both the communications and sensing signals; and
- providing detector means for detecting the sensing signal and, if required, the counter-propagating sensing optical signals effected by the same parameter and for determining the time delay or difference between the signals in order to determine the location of the sensed event.

Preferably further silica waveguides are connected to the first silica waveguide at either or both ends in order to provide insensitive lead waveguides and, if applicable, to add additional delay between the transmissive counter-propagating signals.

In another embodiment the sensing wavelength output port of the wavelength demultiplexing waveguide coupler is terminated with a reflective mirror so as to operate the sensing technique in a reflective mode. Similarly, a mirrored waveguide could be connected to the sensing wavelength output port of the wavelength demultiplexing waveguide coupler.

If only the sensing technique is utilised, preferably the detector means comprises:

- a photodetector for receiving the transmitted or reflected radiation from the sensing signal in the silica waveguide; and
- processing means for receiving signals from the photodetector and analysing the signals in order to register the sensed events.

If the locating technique is utilised as well as the sensing technique, preferably the detector means comprises:

- first and second photodetectors for simultaneously receiving the radiation from the counter-propagating signals in the silica waveguide; and
- processing means for receiving signals from the first and second photodetectors and analysing the signals in order to register the sensed events and determining the time delay or difference between the counter-propagating signals effected from the same disturbance, thus determining the location of the sensed events.

In a preferred embodiment the silica waveguide is a multimoded fibre at the sensing wavelength and the lead waveguides are singlemode fibres at the sensing wavelength.

In a preferred embodiment, but without limitation, the distributed sensing technique is based on a modalmetric technique utilising the fusion splicing of insensitive singlemode fibre to sensitive multimode fibre. [4]

In another preferred embodiment, the transmissive counter-propagating signal method for locating events is employed, and suitable optical devices are employed at one or both ends of the system to detect the signals. [6]

In a preferred embodiment the wavelength multiplexing/demultiplexing (WDM) couplers are 2x1 WDM couplers. In other embodiments they may be any suitable multi-port device, such as 2x2, 3x1, 4x2, etc.

In a preferred embodiment all the optical fibres and fibre devices are connected by fusion splices. In other embodiments the optical fibres and fibre devices may be connected by any suitable or appropriate technique, such as mechanical splices, connectorised leads and through-adaptors, etc.

In other embodiments the WDM couplers may be replaced with alternate wavelength filtering, conditioning, combining, splitting or directing devices.

In other embodiments a plurality of WDM couplers are utilised in a ring topology network, forming junction by-pass arrangements for the sensing signal in order to extend the sensing fibre length beyond one communication node.

Preferably the waveguide comprises at least one optical fibre and/or at least one optical fibre device. In some embodiments of the invention the waveguide may merely comprise an optical fibre without any additional elements. However, the optical fibre can include passive or active elements along its length. Furthermore, the optical fibre can include sensing elements along its length and those sensing elements can comprise devices which will respond to a change in the desired parameter in the environment of application and influence the properties and characteristics of the sensing electromagnetic radiation propagating in the waveguide to thereby provide an indication of the change in the parameter.

Preferably any suitable CW or pulsed single or multiple wavelength source or plurality of sources may be employed. In a preferred embodiment, without limitation, a CW or pulsed coherent laser diode is utilised to supply the optical signal. In an alternate arrangement, multiple light sources, of the same or varying wavelengths, may be used to generate the sensing signal or a plurality of sensing signals.

The preferred embodiments of the present invention offer the potential to utilise all-fibre, low-cost optical devices in conjunction with laser diodes, light emitting diodes, photodetectors, couplers, WDM couplers, isolators and filters.

In the preferred embodiments of the present invention any suitable light source, coupler and photodetector arrangement may be used with the sensor and locating systems. In a preferred embodiment, the required optical properties of the light source are such that light may be launched into and propagated in the singlemode waveguide. For localisation, the light propagated in a singlemode fibre must remain singlemoded during the entire period of travel in the singlemode fibre. Once the light is launched into the multimode fibre from the singlemode fibre, several modes may be excited and the multimoded fibre will be sensitive to various parameters. Once the light is launched back into the singlemode fibre from the multimode fibre, only a single mode is supported and travels to the optical components of the system. Lead-in/lead-out fibre desensitisation and sensor localisation is achieved in this manner. In practical applications, the singlemode fibre should be made sufficiently long to attenuate all cladding modes in order to improve the signal-to-noise ratio. This preferred embodiment applies for both directions of travel of the transmissive counter-propagating optical signals.

Utilisation of properties and characteristics of the electromagnetic radiation propagating in the waveguide sensor enables monitoring to take place in a non-destructive manner. Thus, the sensor is not necessarily damaged, fractured or destroyed in order to monitor and locate the desired parameter.

In the method, according to the preferred embodiment of the invention, electromagnetic radiation at the sensing wavelength is launched into an optical waveguide (single or multi moded), such as an optical fibre, from a light source, such as a pigtailed laser diode, fibre laser or light emitting diode, and propagates along the optical waveguide. The optical waveguide is fusion spliced, or otherwise connected (temporarily or permanently), to one input arm of an optical waveguide wavelength multiplexing light splitter or coupler (single or multi moded) and when the

electromagnetic radiation reaches the coupler the electromagnetic radiation can branch out into the output waveguide arm of the coupler. Simultaneously, electromagnetic radiation at the communications wavelength is launched into another optical waveguide (single or multi moded), such as an optical fibre, from a light source, such as a pigtailed laser diode, fibre laser or light emitting diode, and propagates along the optical waveguide. The optical waveguide is fusion spliced, or otherwise connected (temporarily or permanently), to the second input arm of the wavelength multiplexing coupler and when the electromagnetic radiation reaches the coupler the electromagnetic radiation can likewise branch out into the same output waveguide arm of the coupler as the sensing signal. Thus, the wavelength multiplexing coupler efficiently combines both the sensing and communications signals into a single output waveguide arm. If a wavelength multiplexing coupler with two output arms is used then the unused arm is fractured or otherwise terminated to avoid back-reflections. The output arm of the wavelength multiplexing coupler is fusion spliced, or otherwise connected (temporarily or permanently), directly to the main waveguide transmission link (single or multi moded for the communications signal and multimoded for the sensing signal). Both the communications and sensing signals propagate along the entire length of the waveguide, without interfering with one another, until they reach the opposite end of the link. The main waveguide is then fusion spliced, or otherwise connected (temporarily or permanently), to the input arm of a wavelength demultiplexing coupler and when the signals reach the coupler they are efficiently separated and branched out into two separate output arms of the coupler. The output arms of the wavelength demultiplexing coupler are then terminated at appropriate photodetectors. Appropriate electronics, signal processing schemes and algorithms process the signals from the photodetectors to obtain the desired information.

In a preferred embodiment the WDM couplers are 2x1 WDM couplers. In other embodiments they may be any suitable multi-port device, such as 2x2, 3x1, 4x2, etc.

In other embodiments a plurality of WDM couplers are utilised to form junction by-pass arrangements for the sensing signal in order to extend the sensing fibre length beyond one communication node.

In a preferred embodiment all the optical fibres and fibre devices are connected by fusion splices. In another embodiment the optical fibres and fibre devices are connected by any suitable or appropriate technique, such as mechanical splices, connectorised leads and through-adaptors, etc.

In another embodiment the sensing wavelength output port of the WDM coupler is terminated with a reflective mirror so as to operate the sensing technique in a reflective mode. Similarly, a mirrored fibre could be connected to the output port of the WDM coupler.

In another embodiment, the transmissive counter-propagating signal method for locating events is employed, and suitable optical devices are employed at one or both ends of the system to detect the signals.

In other embodiments the WDM couplers may be replaced with alternate wavelength filtering, conditioning, combining, splitting or directing devices.

Preferably the instrument optical and electronic arrangements will utilise noise minimisation techniques.

Preferably, all the optical and electrical components will be located in a single instrument control box, with individual optical fibre input/output ports.

Optical devices, electro-optic devices, acousto-optic devices, magneto-optic devices and/or integrated optical devices may also be utilised in the system.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will be further illustrated, by way of example, with reference to the following drawings in which:

Figure 1 shows an integrated fibre optic sensing and communications system, utilising the modalmetric sensing technique; [5,6]

Figure 2 shows the results from the sensing arrangement shown in Figure 1 when a vibrational disturbance was applied to a short section of the fibre link; [5]

Figure 3 shows the basic principle of the waveguide transmissive counter-propagating signal method for locating events in fibre optic sensing systems; [6]

Figure 4 shows a combined fibre optic sensing and communications arrangement, utilising a modalmetric sensing technique and the ability to locate disturbances formed by the method of Figure 3; [6]

Figure 5 is a view showing a general embodiment of the present invention for a transmissive sensing arrangement operating over a singlemode optical fibre telecommunication link;

Figure 6 is a view showing a general embodiment of the invention for a reflective sensing arrangement operating over a singlemode optical fibre telecommunication link;

Figure 7 is a view showing a general embodiment of the invention for a two-ended counter-propagating sensing and locating arrangement operating over a singlemode optical fibre telecommunication link;

Figure 8 is a view showing a general embodiment of the invention for a single-ended counter-propagating sensing and locating arrangement operating over a singlemode optical fibre telecommunication link;

Figure 9 is a view showing another general embodiment of the invention for a transmissive sensing arrangement operating over a multimode optical fibre telecommunication link;

Figure 10 is a view showing another general embodiment of the invention for a reflective sensing arrangement operating over a multimode optical fibre telecommunication link;

Figure 11 is a view showing another general embodiment of the invention for a two-ended counter-propagating sensing and locating arrangement operating over a multimode optical fibre telecommunication link;

Figure 12 is a view showing another general embodiment of the invention for a single-ended counter-propagating sensing and locating arrangement operating over a multimode optical fibre telecommunication link;

Figure 13 is a view showing a further general embodiment of the invention, utilising a plurality of WDM couplers in a singlemode optical fibre, three-node, point-to-point network arrangement, forming a junction by-pass arrangement for the sensing signal in order to extend the sensing fibre length beyond one communication node;

Figure 14 is a view showing a further general embodiment of the invention, utilising a plurality of WDM couplers in a multimode optical fibre, three-node, point-to-point network, forming a junction by-pass arrangement for the sensing signal in order to extend the sensing fibre length beyond one communication node;

Figure 15 is a view showing yet another general embodiment of the invention, utilising a transmissive sensing arrangement and a plurality of WDM couplers in an optical fibre ring topology network, forming several junction by-pass arrangements for the sensing signal in order to extend the overall sensing fibre length across the entire ring topology network; and

Figure 16 is a view showing yet another general embodiment of the invention, utilising a counter-propagating sensing and locating arrangement and a plurality of WDM couplers in an optical fibre ring topology network arrangement, forming several junction by-pass arrangements for the sensing signals in order to extend the overall sensing fibre length across the entire ring topology network.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the invention, without imposing any limitations, will be further described with reference to the above mentioned drawings. The drawings and the following embodiments are provided in as general a form as possible to avoid confusion. While it may not be specifically stated or illustrated in the following embodiments and drawings, in the preferred embodiments the following features are utilised, and not intentionally omitted, where appropriate:

- the distributed sensing technique is based on a modalmetric technique utilising the fusion splicing of insensitive singlemode fibre to sensitive multimode fibre;
- the transmissive counter-propagating signal method for locating events is employed, where appropriate, and suitable optical devices are employed at one or both ends of the system to detect and process the signals;
- further silica waveguides are connected to the main silica waveguide communication link at either or both ends in order to provide insensitive lead waveguides and, if applicable, to add additional delay between the transmissive counter-propagating signals;
- any suitable light source, coupler and photodetector arrangement may be used with the sensor and locating systems. In a preferred embodiment, the required optical properties of the light source are such that light may be launched into and propagated in the singlemode waveguide. For localisation, the light propagated in a singlemode fibre must remain singlemoded during the entire period of travel in the singlemode fibre. Once the light is launched into the multimode fibre from the singlemode fibre, several modes may be excited and the multimoded fibre will be sensitive to various parameters. Once the light is launched back into the singlemode fibre from the multimode fibre, only a single mode is supported and travels to the optical components of the system. Lead-in/lead-out fibre desensitisation and sensor localisation is achieved in this manner. In practical applications, the singlemode fibre should be made sufficiently long to attenuate all cladding modes in order to improve the signal-to-noise ratio. This preferred embodiment applies for both directions of travel of the transmissive counter-propagating optical signals where this technique is utilised;
- utilisation of properties and characteristics of the electromagnetic radiation propagating in the waveguide sensor enables monitoring to take place in a non-destructive manner. Thus, the sensor is not necessarily damaged, fractured or destroyed in order to monitor and locate the desired parameter;
- utilisation of all-fibre, low-cost optical devices in conjunction with laser diodes, light emitting diodes, photodetectors, couplers, WDM couplers, isolators and filters;
- the wavelength multiplexing/demultiplexing (WDM) couplers are 2x1 WDM couplers, in other embodiments they may be any suitable multi-port device, such as 2x2, 3x1, 4x2, etc.; and
- the optical fibres and fibre devices are connected by fusion splices. In another embodiments the optical fibres and fibre devices are connected by any suitable or appropriate technique, such as mechanical splices, connectorised leads and through-adaptors, etc.

Figure 1 illustrates the configuration used for the demonstration of a simultaneous fibre optic communications and sensing system. [5,6] The system configuration consisted of the fibre link **1**, either single or multi moded, with standard 3 dB (50% splitting ratio), 2x2 fibre couplers **3a** and **3b** at each end to allow for the multiplexing and demultiplexing of the two wavelengths at the transmitter **2a** and **4a** and receiver ends **2b** and **4b**, respectively. The choice of sensing wavelength was important as the responsivity of the InGaAs detector **2b** in the communications channel needed to be negligible at the sensing wavelength. Thus, the communications channel was chosen to operate at a wavelength of 1300 nm whilst the sensing channel was chosen to operate at either 633 nm or 850 nm. This ensured that inter-channel crosstalk was negligible, as the Si detector **4b** utilised in the sensing channel would not respond to the 1300 nm communications signal.

Figure 2 shows the results from the sensing arrangement shown in Figure 1 when a vibrational disturbance was applied to a short section of the fibre link using a cantilever beam arrangement. The fibre was simply taped longitudinally along the beam length. Results are shown for a 28 km singlemode (SM) link and a 53 km multimode (MM) fibre link. As can be seen, very good signal quality was obtained. In addition, the Fast Fourier Transforms (FFTs) clearly identify the natural frequency of the beam to be ~18 Hz with both links.

Figure 3 shows the basic principle of the waveguide transmissive counter-propagating signal method for locating events in fibre optic sensing systems. [6] The technique relies on the measurement of the time delay or difference between transmissive counter-propagating optical signals affected by the same event in a two-ended fibre arrangement. In this novel arrangement, continuous-wave (CW) optical signals are simultaneously launched, preferably from a single light source, into opposite ends of a sensing optical fibre or set of fibres and simultaneously detected by synchronised photodetectors. Any sensed parameter which acts to alter the counter-propagating signals will effect both signals in the same manner. However, because the effected counter-propagating signals must each continue travelling the remainder of the fibre length to their respective photodetectors there is a resultant time delay or time difference between the detected signals. The time delay is directly proportional to the location of the sensed event along the fibre length referenced from Port 1 according to the following formula:

$$Point\quad of\quad disturbance_{Port1} = \frac{d_x - (v\Delta t)}{2}\ , \tag{1}$$

where d_x is the total length of the optical fibre link, Δt is the resultant time delay or time difference between the detected signals and v is the speed of the optical signal given by c/n_{fibre}, where c is the speed of light in a vacuum (3×10^8 m/s) and n_{fibre} is the effective refractive index of the optical fibre.

Similarly, the point of disturbance referenced from Port 2 is given by:

$$Point\quad of\quad disturbance_{Port2} = \frac{d_x + (v\Delta t)}{2}\ . \tag{2}$$

Therefore, if the time delay or difference is detected and measured, the location of the event can be determined. At the same time, if a compatible sensing mechanism is being employed the sensed event can be quantified and/or identified (ie., strain, vibration, acoustic emission, temperature transients, etc.). In addition, non-sensitive fibre optic delay lines may be connected to the sensing fibre at either or both ends in order to add additional delay between the transmissive counter-propagating signals and to provide insensitive lead fibres. This may assist engineering the technique into a practical working system.

It is interesting to note that this result illustrates that it is required to only know the length of the entire fibre link, d_x , and not the respective lengths of the various sensitive and insensitive fibre regions in the system. This information can be easily obtained at the design and installation stages of a project, or post-installation by the use of an OTDR. Then, once the total length is known and the time delay, Δt, is measured by the system, it is a straight forward calculation using Equations 1 or 2 to determine the location of the sensed event.

Figure 4 shows a combined fibre optic sensing and communications arrangement, utilising a modalmetric sensing technique and the ability to locate disturbances formed by the method of Figure 3. [6] In a practical application of this technique, it will usually be desirable for both launch points of the counter-propagating signals to be at the same physical location. One method in which this can easily be achieved is by using a multi-fibre cable which will effectively form a single-ended system. In this arrangement, one singlemode fibre is utilised as the communications fibre, whilst two fibres, one singlemode and one multimode, are required to set-up the modalmetric intrusion sensor (event detection and location determination) over the specified region of interest (shaded area). A perturbation anywhere along the multimode fibre in the shaded region will generate two counter-propagating perturbation signals. Measuring the time difference in their respective time of arrival at the transmitter end of the link will allow the location of the disturbance to be determined.

Figure 5 is a view showing a general embodiment of the present invention for a transmissive sensing arrangement operating over a singlemode optical fibre telecommunication link. With reference to Figure 5, according to a preferred embodiment of the present invention, coherent laser light at the sensing wavelength 980 nm is launched into a 980 nm singlemode optical fibre **6a** from a pigtailed laser diode with optional integrated isolator **40** and propagates along the optical fibre **6a**. The optical fibre **6a** is fusion spliced **57** to one input arm **6b** of a 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **30** and when the light at the sensing wavelength reaches the coupler **30** it is branched out into the output arm **5a** of the coupler **30**. Simultaneously, laser light at the communications wavelength 1550 nm is launched into a 1550 nm singlemode optical fibre **7a** from a pigtailed laser diode with optional integrated isolator **20** and propagates along the optical fibre **7a**. The optical fibre **7a** is fusion spliced **50** to the second input arm **7b** of the 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **30** and when the light at the communications wavelength reaches the coupler **30** it is likewise branched out into the same output arm **5a** of the coupler **30** as the sensing signal. Thus, the wavelength multiplexing coupler **30** efficiently combines both the sensing and communications signals into a single output coupler arm **5a**. The output arm **5a** of the wavelength multiplexing coupler **30** is then fusion spliced **52** directly to the main 1550 nm singlemode optical fibre transmission link **1000**. Both the communications and sensing signals propagate along the entire length of the 1550 nm singlemode optical fibre transmission link **1000**, without interfering with one another, until they reach the opposite end of the link **1000**. The 1550 nm singlemode optical fibre transmission link **1000** is then fusion spliced **54** to the input arm **5b** of a 980/1550 nm singlemode fibre optic wavelength demultiplexing coupler **32** and when the signals reach the coupler **32** they are efficiently separated and branched out into two separate and respective output arms **6c** and **7c** of the coupler **32**. The 980 nm sensing signal output arm **6c** of the wavelength demultiplexing coupler **32** is then fusion spliced **58** to a 980 nm singlemode fibre **6d** pigtailed InGaAs detector **42**. Similarly, the 1550 nm communications signal output arm **7c** of the wavelength demultiplexing coupler **32** is then fusion spliced **56** to a 1550 nm singlemode fibre **7d** pigtailed InGaAs detector **22**. Finally, appropriate electronics, signal processing schemes and algorithms process the signals from the photodetectors to obtain the desired information.

Figure 6 is a view showing a general embodiment of the invention for a reflective sensing arrangement operating over a singlemode optical fibre telecommunication link. In the

embodiment of Figure 6, according to a preferred arrangement of the present invention, coherent laser light at the sensing wavelength 980 nm is launched into a 980 nm singlemode optical fibre **6a** from a pigtailed laser diode with optional integrated isolator **40** and propagates along the optical fibre **6a**. The optical fibre **6a** is fusion spliced **60** to one input arm **6e** of a 980 nm singlemode coupler **44** and when the light at the sensing wavelength reaches the coupler **44** it is branched out into the output arm **6g** of the coupler **44**. If a wavelength multiplexing coupler with two output arms is used then the unused arm is fractured or otherwise terminated to avoid back-reflections. The light at the sensing wavelength then propagates along optical fibre **6g**. The optical fibre **6g** is fusion spliced **62** to one input arm **6b** of a 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **30** and when the light at the sensing wavelength reaches the coupler **30** it is branched out into the output arm **5a** of the coupler **30**. Simultaneously, laser light at the communications wavelength 1550 nm is launched into a 1550 nm singlemode optical fibre **7a** from a pigtailed laser diode with optional integrated isolator **20** and propagates along the optical fibre **7a**. The optical fibre **7a** is fusion spliced **50** to the second input arm **7b** of the 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **30** and when the light at the communications wavelength reaches the coupler **30** it is likewise branched out into the same output arm **5a** of the coupler **30** as the sensing signal. Thus, the wavelength multiplexing coupler **30** efficiently combines both the sensing and communications signals into a single output coupler arm **5a**. The output arm **5a** of the wavelength multiplexing coupler **30** is then fusion spliced **52** directly to the main 1550 nm singlemode optical fibre transmission link **1000**. Both the communications and sensing signals propagate along the entire length of the 1550 nm singlemode optical fibre transmission link **1000**, without interfering with one another, until they reach the opposite end of the link **1000**. The 1550 nm singlemode optical fibre transmission link **1000** is then fusion spliced **54** to the input arm **5b** of a 980/1550 nm singlemode fibre optic wavelength demultiplexing coupler **32** and when the signals reach the coupler **32** they are efficiently separated and branched out into two separate and respective output arms **6c** and **7c** of the coupler **32**. The 1550 nm communications signal output arm **7c** of the wavelength demultiplexing coupler **32** is then fusion spliced **56** to a 1550 nm singlemode fibre **7d** pigtailed InGaAs detector **22**. The 980 nm sensing signal output arm **6c** of the wavelength demultiplexing coupler **32** is then fusion spliced **64** to a 980 nm singlemode fibre **6h** terminated with a reflective mirror **46**. The sensing signal is thus reflected back in the opposite direction along fibres **6h, 6c, 5b, 1000, 5a, 6b** and **6g**, and branched through coupler **44** to output arm **6f**. Thus the sensing signal propagates along the entire length of the 1550 nm singlemode optical fibre transmission link **1000** twice, effectively doubling sensitivity. The output arm **6f** of the coupler **44** is then fusion spliced **66** to a 980 nm singlemode fibre **6d** pigtailed InGaAs detector **42**. Finally, appropriate electronics, signal processing schemes and algorithms process the signals from the photodetectors to obtain the desired information.

Figure 7 is a view showing another general embodiment of the invention for a two-ended counter-propagating sensing and locating arrangement, according to the method shown in Figure 3, operating over a singlemode optical fibre telecommunication link. A 980 nm counter-propagating sensing system **300** is used to launch a sensing signal in one direction of the 1550 nm singlemode optical fibre transmission link **1000** and the system **300** is suitably time-synchronised with a second 980 nm counter-propagating sensing system **320** launching a sensing signal in the opposite direction of the 1550 nm singlemode optical fibre transmission link **1000**. Any disturbance that acts to alter the counter-propagating sensing signals along link **1000** will effect both signals in the same manner. However, because the effected counter-propagating signals must each continue travelling the remainder of the fibre length to their respective photodetectors in systems **300** and **320** there is a resultant time delay or time difference between the detected signals. The time delay is directly proportional to the location of the sensed event along the fibre length, as described

earlier. Time synchronisation between system **300** and **320** is important in determining the time difference between the counter-propagating signals.

Figure 8 is a view showing yet another general embodiment of the invention for a single-ended counter-propagating sensing and locating arrangement, according to the method shown in Figure 4, operating over a singlemode optical fibre telecommunication link. A single-ended 980 nm counter-propagating sensing system **350** is used to simultaneously launch, propagate and monitor two counter-propagating sensing signals in the 1550 nm singlemode optical fibre transmission link **1000** fusion spliced **74** to another optical fibre (single or multi moded) in the same or nearby cable **1200**. Any disturbance that acts to alter the counter-propagating sensing signals along links **1000** and/or **1200** will effect both signals in the same manner. However, because the effected counter-propagating signals must each continue travelling the remainder of the fibre length to their respective photodetectors in system **350** there is a resultant time delay or time difference between the detected signals. The time delay is directly proportional to the location of the sensed event along the fibre length, as described earlier. Time synchronisation in this case can be easily achieved by utilising a common signal acquisition system.

Figure 9 is a view showing another general embodiment of the present invention for a transmissive sensing arrangement operating over a multimode optical fibre telecommunication link. With reference to Figure 9, according to another preferred embodiment of the present invention, coherent laser light at the sensing wavelength 1310 nm is launched into a 1310 nm singlemode optical fibre **8a** from a pigtailed laser diode with optional integrated isolator **41** and propagates along the optical fibre **8a**. The optical fibre **8a** is fusion spliced **84** to one input arm **8b** of a 850/1310 nm multimode fibre optic wavelength multiplexing coupler **34** and when the light at the sensing wavelength reaches the coupler **34** it is branched out into the output arm **5c** of the coupler **34**. Simultaneously, laser light at the communications wavelength 850 nm is launched into a multimode optical fibre **9a** from a pigtailed laser diode with optional integrated isolator **25** and propagates along the optical fibre **9a**. The optical fibre **9a** is fusion spliced **80** to the second input arm **9b** of the 850/1310 nm multimode fibre optic wavelength multiplexing coupler **34** and when the light at the communications wavelength reaches the coupler **34** it is likewise branched out into the same output arm **5c** of the coupler **34** as the sensing signal. Thus, the wavelength multiplexing coupler **34** efficiently combines both the sensing and communications signals into a single output coupler arm **5c**. The output arm **5c** of the wavelength multiplexing coupler **34** is then fusion spliced **81** directly to the main multimode optical fibre transmission link **1500**. Both the communications and sensing signals propagate along the entire length of the multimode optical fibre transmission link **1500**, without interfering with one another, until they reach the opposite end of the link **1500**. The multimode optical fibre transmission link **1500** is then fusion spliced **82** to the input arm **5d** of a 850/1310 nm multimode fibre optic wavelength demultiplexing coupler **36** and when the signals reach the coupler **36** they are efficiently separated and branched out into two separate and respective output arms **8c** and **9c** of the coupler **36**. The 1310 nm sensing signal output arm **8c** of the wavelength demultiplexing coupler **36** is then fusion spliced **88** to a 1310 nm singlemode fibre **8d** pigtailed InGaAs detector **43**. Similarly, the 850 nm communications signal output arm **9c** of the wavelength demultiplexing coupler **36** is then fusion spliced **83** to a multimode fibre **9d** pigtailed or receptacled Si detector **27**. Finally, appropriate electronics, signal processing schemes and algorithms process the signals from the photodetectors to obtain the desired information.

Figure 10 is a view showing another general embodiment of the invention for a reflective sensing arrangement operating over a multimode optical fibre telecommunication link. In the embodiment of Figure 10, according to another preferred arrangement of the present invention, coherent laser light at the sensing wavelength 1310 nm is launched into a 1310 nm singlemode optical fibre **8a** from a pigtailed laser diode with optional integrated isolator **41** and propagates along the optical

fibre **8a**. The optical fibre **8a** is fusion spliced **86** to one input arm **8e** of a 1310 nm singlemode coupler **45** and when the light at the sensing wavelength reaches the coupler **45** it is branched out into the output arm **8g** of the coupler **45**. If a coupler with two output arms is used then the unused arm is fractured or otherwise terminated to avoid back-reflections. The light at the sensing wavelength then propagates along optical fibre **8g**. The optical fibre **8g** is fusion spliced **87** to one input arm **8b** of a 850/1310 nm multimode fibre optic wavelength multiplexing coupler **34** and when the light at the sensing wavelength reaches the coupler **34** it is branched out into the output arm **5c** of the coupler **34**. If a wavelength multiplexing coupler with two output arms is used then the unused arm is fractured or otherwise terminated to avoid back-reflections. Simultaneously, laser light at the communications wavelength 850 nm is launched into a multimode optical fibre **9a** from a pigtailed laser diode with optional integrated isolator **25** and propagates along the optical fibre **9a**. The optical fibre **9a** is fusion spliced **80** to the second input arm **9b** of the 850/1310 nm multimode fibre optic wavelength multiplexing coupler **34** and when the light at the communications wavelength reaches the coupler **34** it is likewise branched out into the same output arm **5c** of the coupler **34** as the sensing signal. Thus, the wavelength multiplexing coupler **34** efficiently combines both the sensing and communications signals into a single output coupler arm **5c**. The output arm **5c** of the wavelength multiplexing coupler **34** is then fusion spliced **81** directly to the main multimode optical fibre transmission link **1500**. Both the communications and sensing signals propagate along the entire length of the multimode optical fibre transmission link **1500**, without interfering with one another, until they reach the opposite end of the link **1500**. The multimode optical fibre transmission link **1500** is then fusion spliced **82** to the input arm **5d** of a 850/1310 nm multimode fibre optic wavelength demultiplexing coupler **36** and when the signals reach the coupler **36** they are efficiently separated and branched out into two separate and respective output arms **8c** and **9c** of the coupler **36**. The 850 nm communications signal output arm **9c** of the wavelength demultiplexing coupler **36** is then fusion spliced **83** to a multimode fibre **9d** pigtailed or receptacled Si detector **27**. The 1310 nm sensing signal output arm **8c** of the wavelength demultiplexing coupler **36** is then fusion spliced **88** to a 1310 nm singlemode or multimode fibre **8h** terminated with a reflective mirror **47**. The sensing signal is thus reflected back in the opposite direction along fibres **8h, 8c, 5d, 1500, 5c, 8b** and **8g**, and branched through coupler **45** to output arm **8f**. Thus the sensing signal propagates along the entire length of the multimode optical fibre transmission link **1500** twice, effectively doubling sensitivity. The output arm **8f** of the coupler **45** is then fusion spliced **89** to a 1310 nm singlemode fibre **8d** pigtailed InGaAs detector **43**. Finally, appropriate electronics, signal processing schemes and algorithms process the signals from the photodetectors to obtain the desired information.

Figure 11 is a view showing another general embodiment of the invention for a two-ended counter-propagating sensing and locating arrangement, according to the method shown in Figure 3, operating over a multimode optical fibre telecommunication link. A 1310 nm counter-propagating sensing system **400** is used to launch a sensing signal in one direction of the main multimode optical fibre transmission link **1500** and the system **400** is suitably time-synchronised with a second 1310 nm counter-propagating sensing system **420** launching a sensing signal in the opposite direction of the main multimode optical fibre transmission link **1500**. Any disturbance that acts to alter the counter-propagating sensing signals along link **1500** will effect both signals in the same manner. However, because the effected counter-propagating signals must each continue travelling the remainder of the fibre length to their respective photodetectors in systems **400** and **420** there is a resultant time delay or time difference between the detected signals. The time delay is directly proportional to the location of the sensed event along the fibre length, as described earlier. Time synchronisation between system **400** and **420** is important in determining the time difference between the counter-propagating signals.

Figure 12 is a view showing another general embodiment of the invention for a single-ended counter-propagating sensing and locating arrangement, according to the method shown in Figure

4, operating over a multimode optical fibre telecommunication link. A single-ended 1310 nm counter-propagating sensing system **450** is used to simultaneously launch, propagate and monitor two counter-propagating sensing signals in the main multimode optical fibre transmission link **1500** fusion spliced **94** to another optical fibre (single or multi moded) in the same or nearby cable **1700**. Any disturbance that acts to alter the counter-propagating sensing signals along links **1500** and/or **1700** will effect both signals in the same manner. However, because the effected counter-propagating signals must each continue travelling the remainder of the fibre length to their respective photodetectors in system **450** there is a resultant time delay or time difference between the detected signals. The time delay is directly proportional to the location of the sensed event along the fibre length, as described earlier. Time synchronisation in this case can be easily achieved by utilising a common signal acquisition system.

Figure 13 is a view showing a further general embodiment of the invention, utilising a plurality of WDM couplers in a singlemode optical fibre, three-node, point-to-point network arrangement, forming a junction by-pass arrangement for the sensing signal in order to extend the sensing fibre length beyond one communication node. With reference to Figure 13, according to a further preferred embodiment of the present invention, starting at Communications Node 1 coherent laser light at the sensing wavelength 980 nm is launched into a 980 nm singlemode optical fibre **16a** from a pigtailed laser diode with optional integrated isolator **140** and propagates along the optical fibre **16a**. The optical fibre **16a** is fusion spliced **157** to one input arm **16b** of a 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **130** and when the light at the sensing wavelength reaches the coupler **130** it is branched out into the output arm **15a** of the coupler **130**. Simultaneously, at Communications Node 1 laser light at the communications wavelength 1550 nm is launched into a 1550 nm singlemode optical fibre **17a** from a pigtailed laser diode with optional integrated isolator **120** and propagates along the optical fibre **17a**. The optical fibre **17a** is fusion spliced **150** to the second input arm **17b** of the 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **130** and when the light at the communications wavelength reaches the coupler **130** it is likewise branched out into the same output arm **15a** of the coupler **130** as the sensing signal. Thus, the wavelength multiplexing coupler **130** efficiently combines both the sensing and communications signals into a single output coupler arm **15a**. The output arm **15a** of the wavelength multiplexing coupler **130** is then fusion spliced **152** directly to the main 1550 nm singlemode optical fibre transmission link **2000**. Both the communications and sensing signals propagate along the entire length of the 1550 nm singlemode optical fibre transmission link **2000**, without interfering with one another, until they reach the opposite end of the link **2000**. The 1550 nm singlemode optical fibre transmission link **2000** is then fusion spliced **154** to the input arm **15b** of a 980/1550 nm singlemode fibre optic wavelength demultiplexing coupler **132** and when the signals reach the coupler **132** they are efficiently separated and branched out into two separate and respective output arms **16c** and **17c** of the coupler **132**. The 1550 nm communications signal output arm **17c** of the wavelength demultiplexing coupler **132** is then fusion spliced **156** to a 1550 nm singlemode fibre **17d** pigtailed InGaAs detector **122** at Communications Node 2, where appropriate electronics, signal processing schemes and algorithms process the signals from the photodetector **122** to obtain the desired communications information. The 980 nm sensing signal output arm **16c** of the wavelength demultiplexing coupler **132** is then fusion spliced **158** to a 980 nm or 1550 nm singlemode optical fibre **2001** which acts to by-pass Communications Node 2 so that the sensing signal continuous propagating towards Communications Node 3. Continuing on, the sensing signal thus propagates along junction by-pass fibre **2001** until fibre **2001** is fusion spliced **257** to one input arm **116b** of a 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **230** and when the light at the sensing wavelength reaches the coupler **230** it is branched out into the output arm **115a** of the coupler **230**. Simultaneously, at Communications Node 2 laser light at the communications wavelength 1550 nm is launched into a 1550 nm singlemode optical fibre **117a** from a pigtailed laser diode with

optional integrated isolator **220** and propagates along the optical fibre **117a**. The optical fibre **117a** is fusion spliced **250** to the second input arm **117b** of the 980/1550 nm singlemode fibre optic wavelength multiplexing coupler **230** and when the light at the communications wavelength reaches the coupler **230** it is likewise branched out into the same output arm **115a** of the coupler **230** as the sensing signal. Thus, the wavelength multiplexing coupler **230** efficiently combines both the sensing and communications signals into a single output coupler arm **115a**. The output arm **115a** of the wavelength multiplexing coupler **230** is then fusion spliced **252** directly to the second main 1550 nm singlemode optical fibre transmission link **2002**. Both the communications and sensing signals propagate along the entire length of the 1550 nm singlemode optical fibre transmission link **2002**, without interfering with one another, until they reach the opposite end of the link **2002**. The 1550 nm singlemode optical fibre transmission link **2002** is then fusion spliced **254** to the input arm **115b** of a 980/1550 nm singlemode fibre optic wavelength demultiplexing coupler **232** and when the signals reach the coupler **232** they are efficiently separated and branched out into two separate and respective output arms **116c** and **117c** of the coupler **232**. The 1550 nm communications signal output arm **117c** of the wavelength demultiplexing coupler **232** is then fusion spliced **256** to a 1550 nm singlemode fibre **117d** pigtailed InGaAs detector **222** at Communications Node 3. Similarly, the 980 nm sensing signal output arm **116c** of the wavelength demultiplexing coupler **232** is then fusion spliced **258** to a 980 nm singlemode fibre **116d** pigtailed InGaAs detector **242**. Finally, appropriate electronics, signal processing schemes and algorithms at Communications Node 3 process the signals from the photodetectors to obtain the desired information. In this method, the sensing signal was propagated along two optical fibre links **2000** and **2002**, while still utilising only one transmitter **140** end and one detector **242** end.

At the 980 nm sensing wavelength it is possible to also use true multimode fibre in place of the singlemode fibres **2000**, **2001** and **2002** if the communications system was operating over a multimode link.

Figure 14 is a view showing a further general embodiment of the invention, utilising a plurality of WDM couplers in a multimode optical fibre, three-node, point-to-point network, forming a junction by-pass arrangement for the sensing signal in order to extend the sensing fibre length beyond one communication node. With reference to Figure 14, according to a further preferred embodiment of the present invention, starting at Communications Node 1 coherent laser light at the sensing wavelength 1310 nm is launched into a multimode optical fibre **18a** from a pigtailed laser diode with optional integrated isolator **141** and propagates along the optical fibre **18a**. The optical fibre **18a** is fusion spliced **184** to one input arm **18b** of a 850/1310 nm multimode fibre optic wavelength multiplexing coupler **134** and when the light at the sensing wavelength reaches the coupler **134** it is branched out into the output arm **15c** of the coupler **134**. Simultaneously, at Communications Node 1 laser light at the communications wavelength 850 nm is launched into a multimode optical fibre **19a** from a pigtailed laser diode with optional integrated isolator **125** and propagates along the optical fibre **19a**. The optical fibre **19a** is fusion spliced **180** to the second input arm **19b** of the 850/1310 nm multimode fibre optic wavelength multiplexing coupler **134** and when the light at the communications wavelength reaches the coupler **134** it is likewise branched out into the same output arm **15c** of the coupler **134** as the sensing signal. Thus, the wavelength multiplexing coupler **134** efficiently combines both the sensing and communications signals into a single output coupler arm **15c**. The output arm **15c** of the wavelength multiplexing coupler **134** is then fusion spliced **181** directly to the main multimode optical fibre transmission link **2150**. Both the communications and sensing signals propagate along the entire length of the multimode optical fibre transmission link **2150**, without interfering with one another, until they reach the opposite end of the link **2150**. The multimode optical fibre transmission link **2150** is then fusion spliced **182** to the input arm **15d** of a 850/1310 nm multimode fibre optic wavelength demultiplexing coupler **136** and when the signals reach the coupler **136** they are efficiently separated and branched out into two separate and respective output arms **18c** and **19c** of the

coupler **136**. The 850 nm communications signal output arm **19c** of the wavelength demultiplexing coupler **136** is then fusion spliced **183** to a multimode fibre **19d** pigtailed or receptacled Si detector **127** at Communications Node 2, where appropriate electronics, signal processing schemes and algorithms process the signals from the photodetector **127** to obtain the desired communications information. The 1310 nm sensing signal output arm **18c** of the wavelength demultiplexing coupler **136** is then fusion spliced **188** to a multimode or 1310 nm singlemode optical fibre **2160** which acts to by-pass Communications Node 2 so that the sensing signal continuous propagating towards Communications Node 3. Continuing on, the sensing signal thus propagates along junction by-pass fibre **2160** until fibre **2160** is fusion spliced **284** to one input arm **118b** of a 850/1310 nm multimode fibre optic wavelength multiplexing coupler **234** and when the light at the sensing wavelength reaches the coupler **234** it is branched out into the output arm **115c** of the coupler **234**. Simultaneously, at Communications Node 2 laser light at the communications wavelength 850 nm is launched into a multimode optical fibre **119a** from a pigtailed laser diode with optional integrated isolator **225** and propagates along the optical fibre **119a**. The optical fibre **119a** is fusion spliced **280** to the second input arm **119b** of the 850/1310 nm multimode fibre optic wavelength multiplexing coupler **234** and when the light at the communications wavelength reaches the coupler **234** it is likewise branched out into the same output arm **115c** of the coupler **234** as the sensing signal. Thus, the wavelength multiplexing coupler **234** efficiently combines both the sensing and communications signals into a single output coupler arm **115c**. The output arm **115c** of the wavelength multiplexing coupler **234** is then fusion spliced **281** directly to the second main multimode optical fibre transmission link **2170**. Both the communications and sensing signals propagate along the entire length of the multimode optical fibre transmission link **2170**, without interfering with one another, until they reach the opposite end of the link **2170**. The multimode optical fibre transmission link **2170** is then fusion spliced **282** to the input arm **115d** of a 850/1310 nm multimode fibre optic wavelength demultiplexing coupler **236** and when the signals reach the coupler **236** they are efficiently separated and branched out into two separate and respective output arms **118c** and **119c** of the coupler **236**. The 850 nm communications signal output arm **119c** of the wavelength demultiplexing coupler **236** is then fusion spliced **283** to a multimode fibre **119d** pigtailed or receptacled Si detector **227** at Communications Node 3. Similarly, the 1310 nm sensing signal output arm **118c** of the wavelength demultiplexing coupler **236** is then fusion spliced **288** to a multimode or 1310 nm singlemode fibre **118d** pigtailed InGaAs detector **243**. Finally, appropriate electronics, signal processing schemes and algorithms at Communications Node 3 process the signals from the photodetectors to obtain the desired information. In this method, the sensing signal was propagated along two optical fibre links **2150** and **2170**, while still utilising only one transmitter **141** end and one detector **243** end.

Figure 15 is a view showing yet another general embodiment of the invention, utilising a transmissive sensing arrangement and a plurality of WDM couplers in an optical fibre ring topology network, forming several junction by-pass arrangements for the sensing signal in order to extend the overall sensing fibre length across the entire ring topology network. In this arrangement, ring topology network (RTN) nodes **500, 502, 504, 506, 508** and **510** are interconnected via optical fibre (single or multi moded) links **600, 602, 604, 606, 608** and **610** by a logical sequence of appropriate WDM couplers **550, 552, 554, 556, 558, 560, 562, 564, 566, 568, 570** and **572**. Meanwhile, a sensing signal is launched from a pigtailed laser diode with optional isolator **520** around the network fibres **600, 602, 604, 606, 608** and **610** by the same logical sequence of appropriate WDM couplers **550, 552, 554, 556, 558, 560, 562, 564, 566, 568, 570** and **572** and junction by-pass fibres (single or multi moded) **650, 652, 654, 656** and **658** until the signal is finally received at detector **540**, in a similar fashion as that described in detail for Figures 13 and 14. The advantage of this arrangement is that the overall sensing fibre length was extended

across the entire ring topology network, while still utilising only one transmitter **520** end and one detector **540** end.

Figure 16 is a view showing yet another general embodiment of the invention, utilising a counter-propagating sensing and locating arrangement and a plurality of WDM couplers in an optical fibre ring topology network arrangement, forming several junction by-pass arrangements for the sensing signals in order to extend the overall sensing fibre length across the entire ring topology network. In this arrangement, ring topology network (RTN) nodes **700, 702, 704, 706, 708** and **710** are interconnected via optical fibre (single or multi moded) links **800, 802, 804, 806, 808** and **810** by a logical sequence of appropriate WDM couplers **750, 752, 754, 756, 758, 760, 762, 764, 766, 768, 770** and **772**. Meanwhile, a counter-propagating sensing system **720** simultaneously launches counter-propagating sensing signals around the network fibres **800, 802, 804, 806, 808** and **810** by the same logical sequence of appropriate WDM couplers **750, 752, 754, 756, 758, 760, 762, 764, 766, 768, 770** and **772** and junction by-pass fibres (single or multi moded) **850, 852, 854, 856** and **858** until the signals are finally received at synchronised detectors in the counter-propagating sensing system **720**, in a similar fashion as that described in detail in the other figures. The advantage of this arrangement is that the overall sensing fibre length was extended across the entire ring topology network, while utilising only a single instrument control box, with individual optical fibre input/output ports.

APPLICATIONS OF THE PREFERRED EMBODIMENTS

Communications using optical fibres have a number of attractive features and advantages over conventional communication means, and their performance has been proven over the past two decades. The value offered by these systems has now been augmented by the ability to simultaneously monitor, in real-time, the integrity of the cable, as well as any structure or material near the cable or to which the cable is attached. This attractive and useful new feature should increase the demand for the technology.

Not inclusive, but indicatively, the following examples illustrates the applications in which a combined communications and sensing (dual) system may be used:

- Any fibre optic communications systems which need to be monitored against and detect intrusion, tampering or tapping-off of information from the optical fibres, such as:
  - Singlemode or multimode information technology (IT) networks and links
  - Singlemode local area networks (LANs)
  - Multimode local area networks (LANs)
  - Singlemode wide area networks (WANs)
  - Multimode wide area networks (WANs)
  - Short-haul telecommunications
  - Long-haul telecommunications
  - Private fibre optic links and networks
  - Public fibre optic links and networks
  - Commercial fibre optic links and networks
  - Government fibre optic links and networks
  - Military fibre optic links and networks
  - Defence fibre optic links and networks
  - Embassy fibre optic links and networks

    - Industrial fibre optic links and networks
    - Financial organisation fibre optic links and networks
- Any fibre optic communications systems which are also utilised for sensing applications, including:
    - Public telecommunications
    - Private telecommunications
    - Information technology networks
    - National security
    - Industrial security
    - Law enforcement
    - Counter-intelligence
    - Physical perimeter security
    - Intrusion detection & location
    - Pipeline integrity monitoring
    - Pipeline third party interference detection & location
    - Pipeline leak detection & location
    - Public road authorities
    - Private road ventures
    - Railway authorities and freight operators
    - Road transport operators
- Any fibre optic sensing systems which are also utilised for telecommunications, including:
    - Public telecommunications
    - Private telecommunications
    - Information technology networks
    - National security
    - Industrial security
    - Law enforcement
    - Counter-intelligence
    - Physical perimeter security
    - Intrusion detection & location
    - Pipeline integrity monitoring
    - Pipeline third party interference detection & location
    - Pipeline leak detection & location
    - Land and offshore building & construction structural integrity monitoring & design
    - Machine performance monitoring & design
    - Rail stock monitoring (Flat spot detection)
    - Power generation and transmission companies
    - Petro-chemical & industrial plant monitoring & design organisations
    - Aerospace/aviation design and maintenance organisations
    - Public road authorities
    - Private road ventures
    - Railway authorities and freight operators

- Road transport operators
- Airline operators
- Mining companies
- Earthquake monitoring organisations
- Oceanographic companies

Since modifications within the spirit and scope of the invention may readily be effected by persons skilled within the art, it is to be understood that this invention is not limited to the particular embodiments described by way of example hereinabove.

FUTURE FIBRE TECHNOLOGIES PTY. LTD.

By EDWARD TAPANES, Director of FFT Pty. Ltd. 30 April 1999

(Name of Applicant) (Date)

(BLOCK LETTERS)

Figur 1

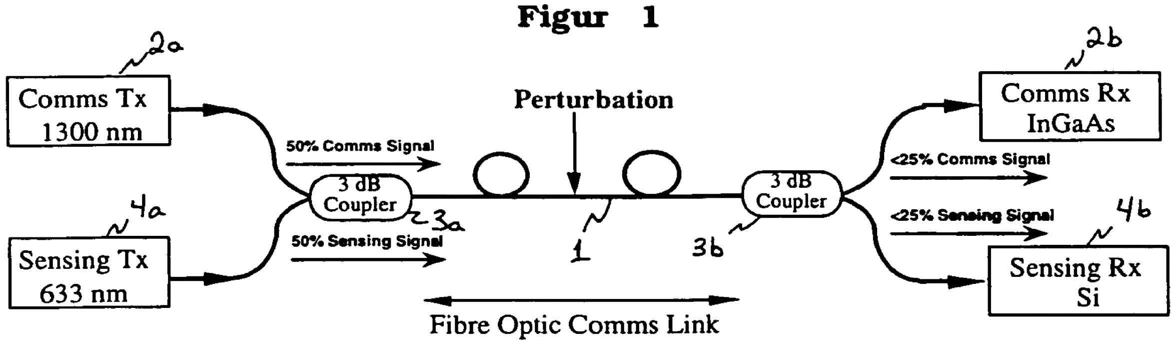


Figure 2

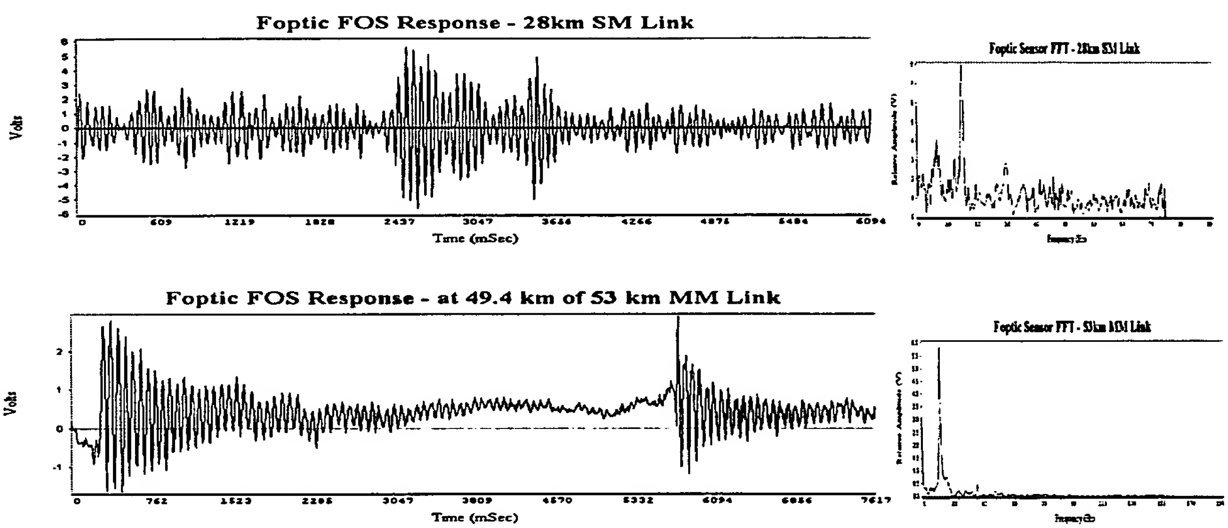


Figure 3

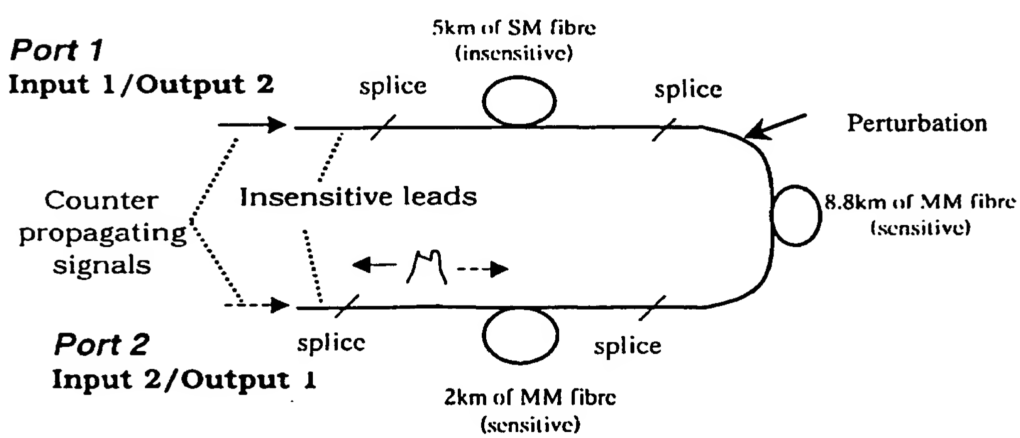


Figure 4

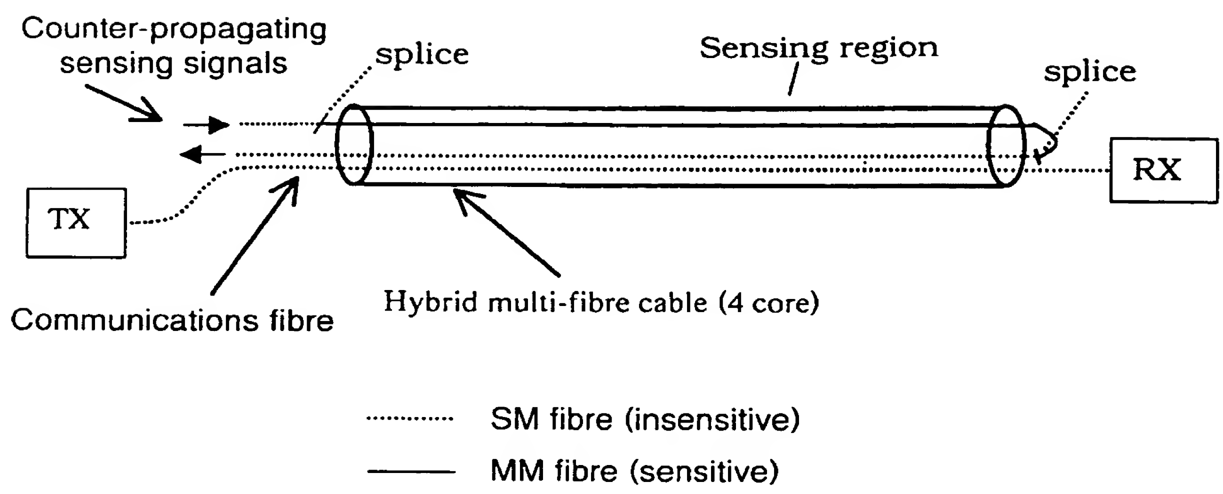


Figure 5

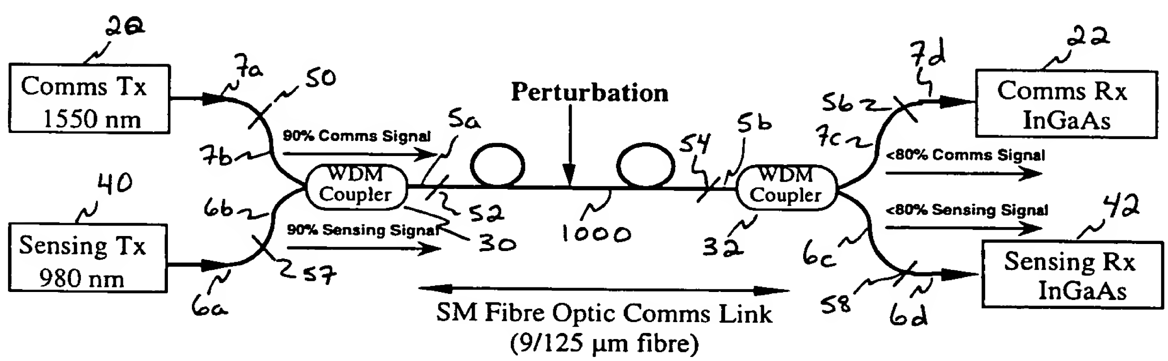


Figure 6

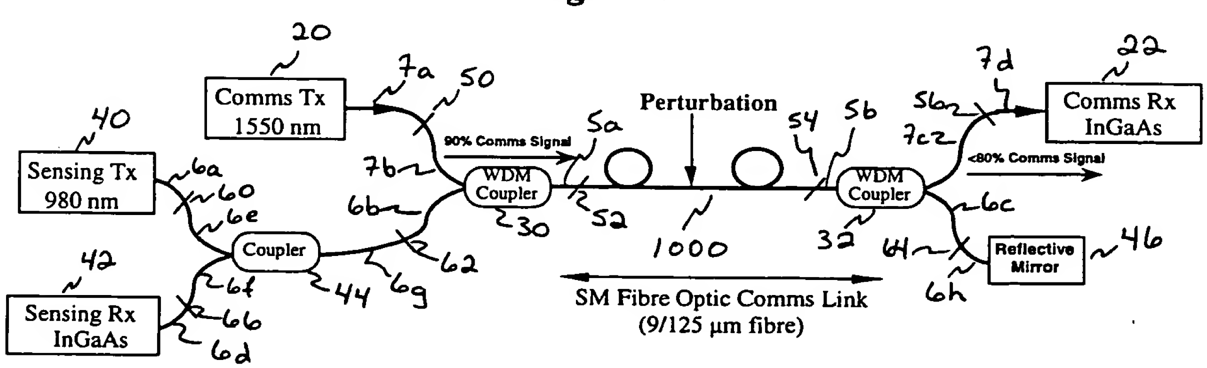


Figure 7

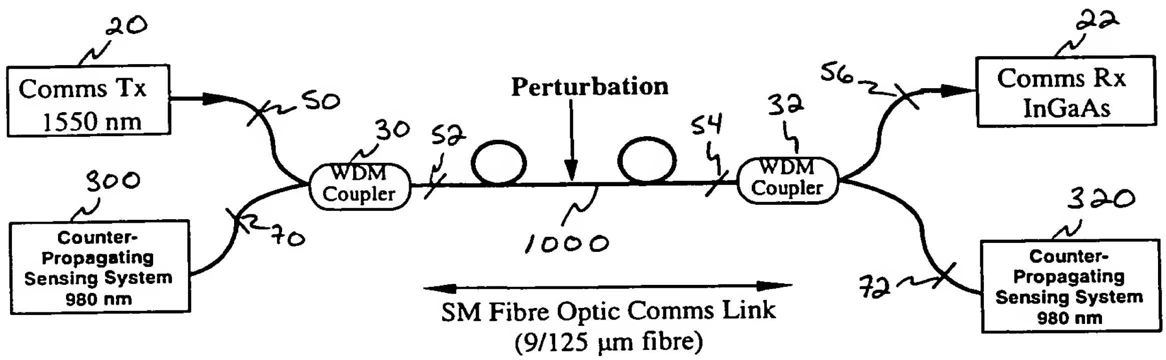


Figure 8

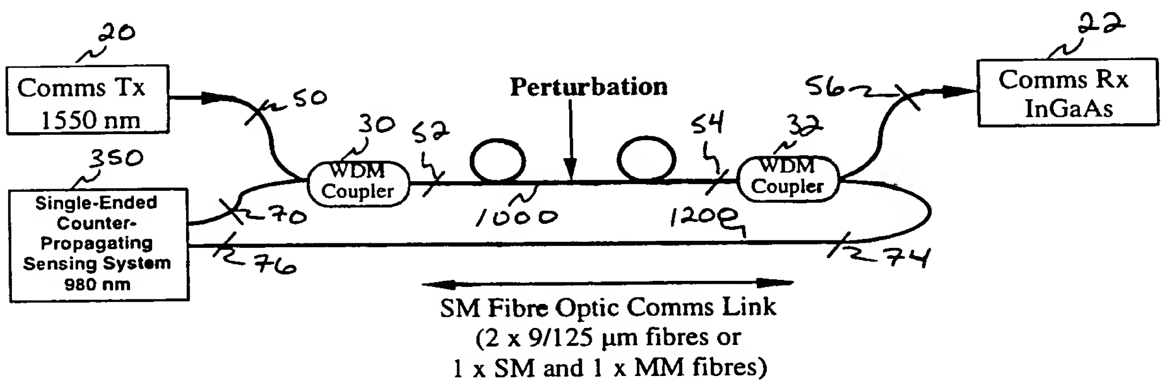


Figure 9

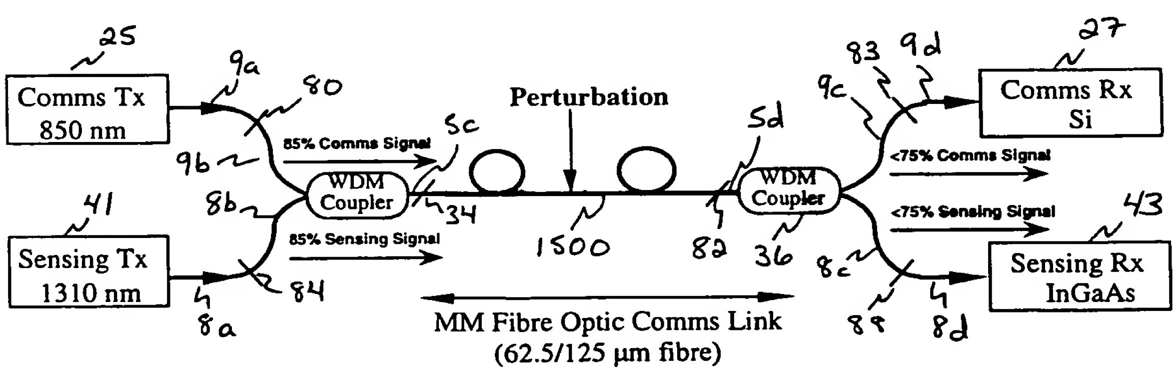


Figure 10

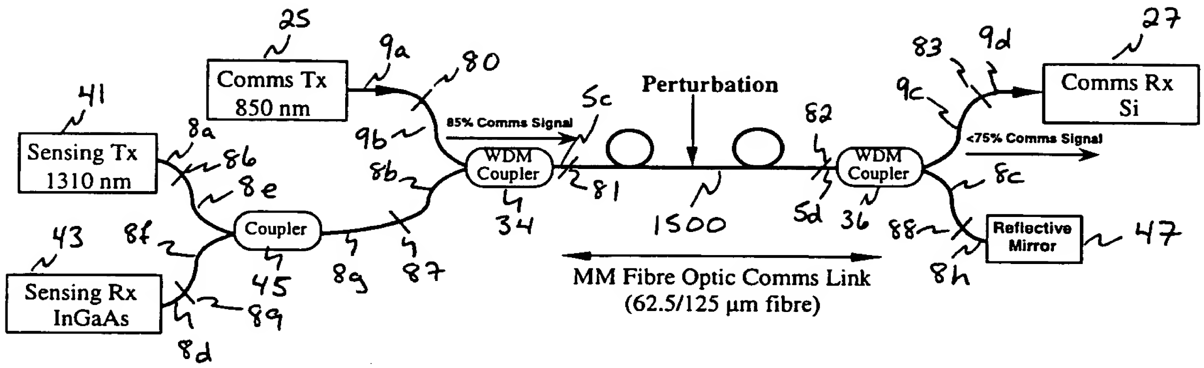


Figure 11

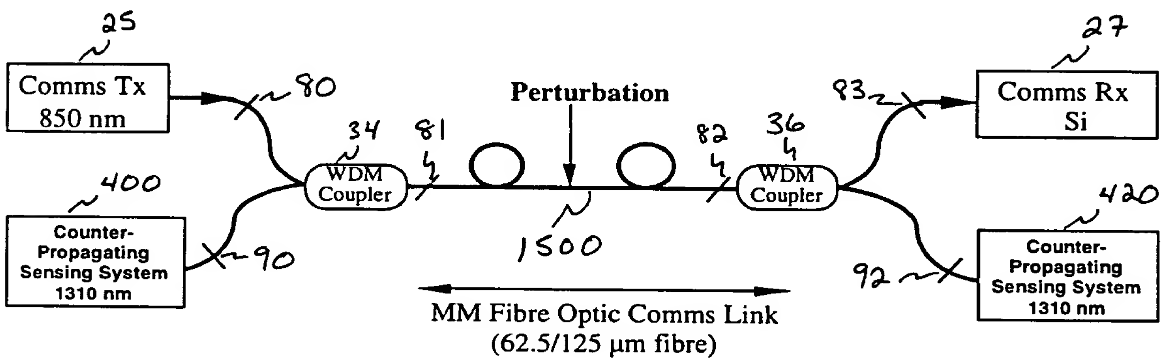


Figure 12

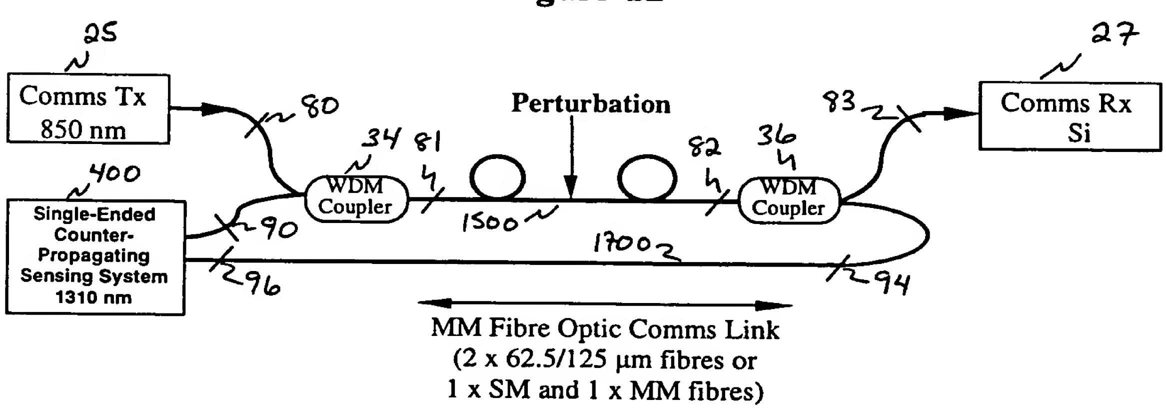


Figure 13

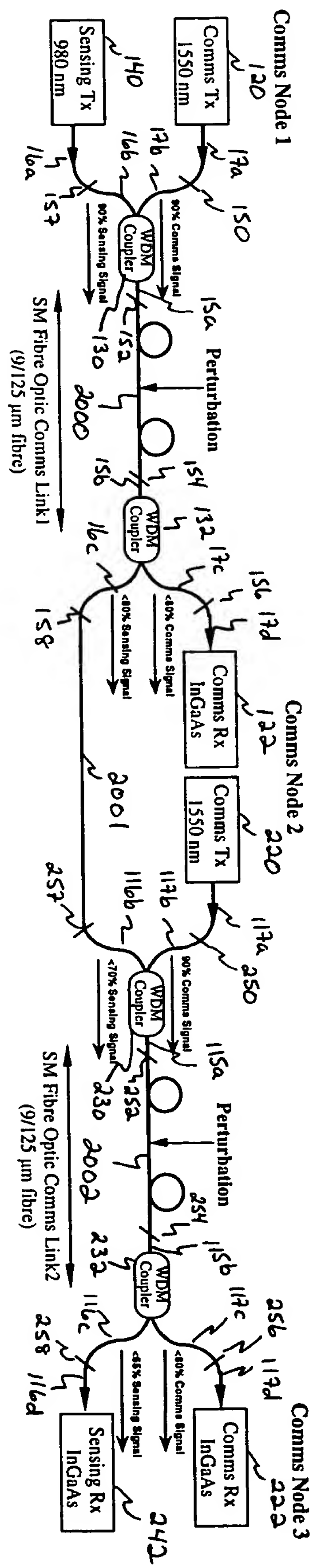

Comms Node 1
Comms Tx
1550 nm
120
Sensing Tx
980 nm
140
17a
17b
16a
16b
150
157
90% Comms Signal
90% Sensing Signal
WDM
Coupler
15a
152
130
Perturbation
2000
SM Fibre Optic Comms Link1
(9/125 μm fibre)
154
156
132
WDM
Coupler
16c
17c
156
17d
158
<80% Comms Signal
<80% Sensing Signal
Comms Node 2
Comms Rx
InGaAs
122
Comms Tx
1550 nm
220
2001
117a
117b
116b
257
250
90% Comms Signal
<70% Sensing Signal
WDM
Coupler
115a
252
230
Perturbation
2002
SM Fibre Optic Comms Link2
(9/125 μm fibre)
254
232
115b
WDM
Coupler
117c
116c
256
117d
258
116d
<80% Comms Signal
<65% Sensing Signal
Comms Node 3
Comms Rx
InGaAs
222
Sensing Rx
InGaAs
242

Figure 14

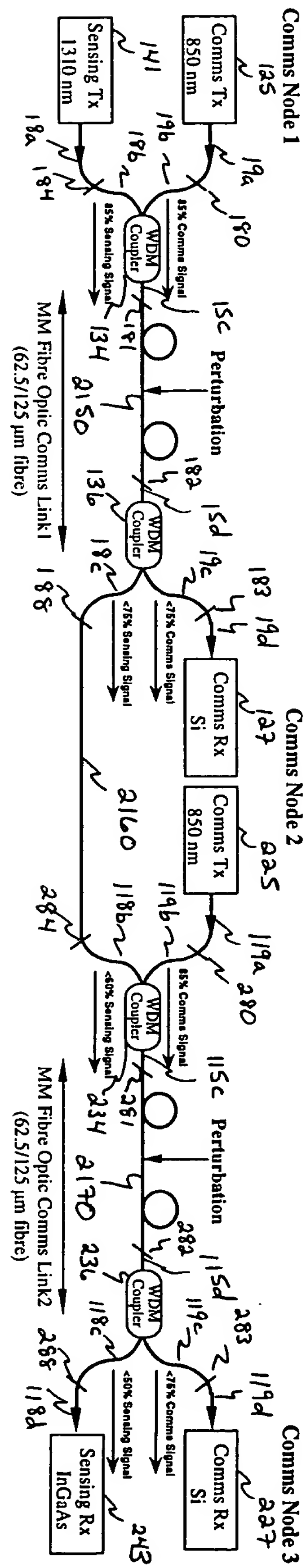

Comms Node 1
Comms Tx
850 nm
Sensing Tx
1310 nm
85% Comms Signal
WDM
Coupler
85% Sensing Signal
Perturbation
MM Fibre Optic Comms Link1
(62.5/125 µm fibre)
WDM
Coupler
<75% Comms Signal
<75% Sensing Signal
Comms Rx
Si
Comms Node 2
Comms Tx
850 nm
85% Comms Signal
WDM
Coupler
<60% Sensing Signal
Perturbation
MM Fibre Optic Comms Link2
(62.5/125 µm fibre)
WDM
Coupler
<75% Comms Signal
<60% Sensing Signal
Comms Rx
Si
Sensing Rx
InGaAs
Comms Node 3

Figure 15

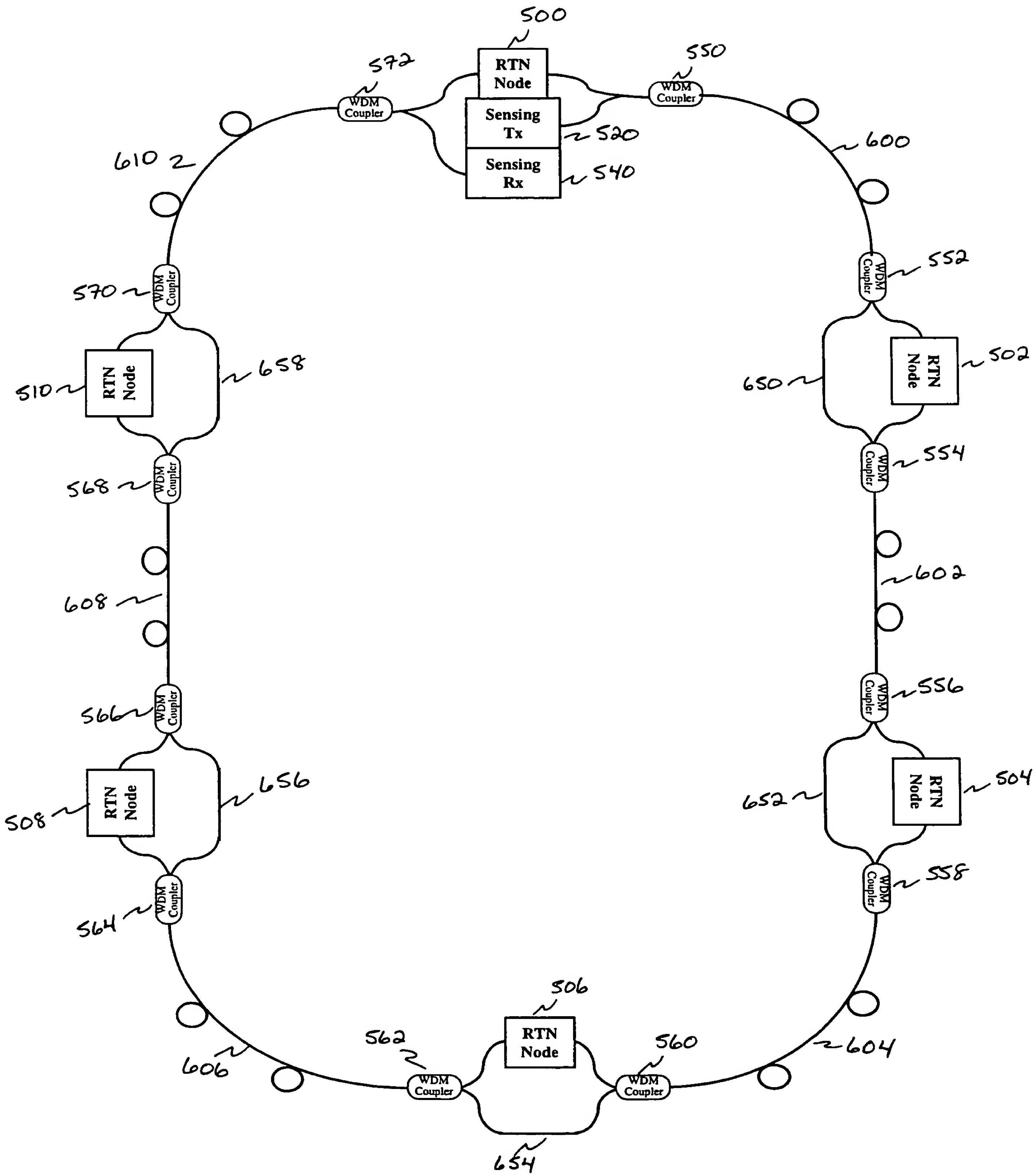
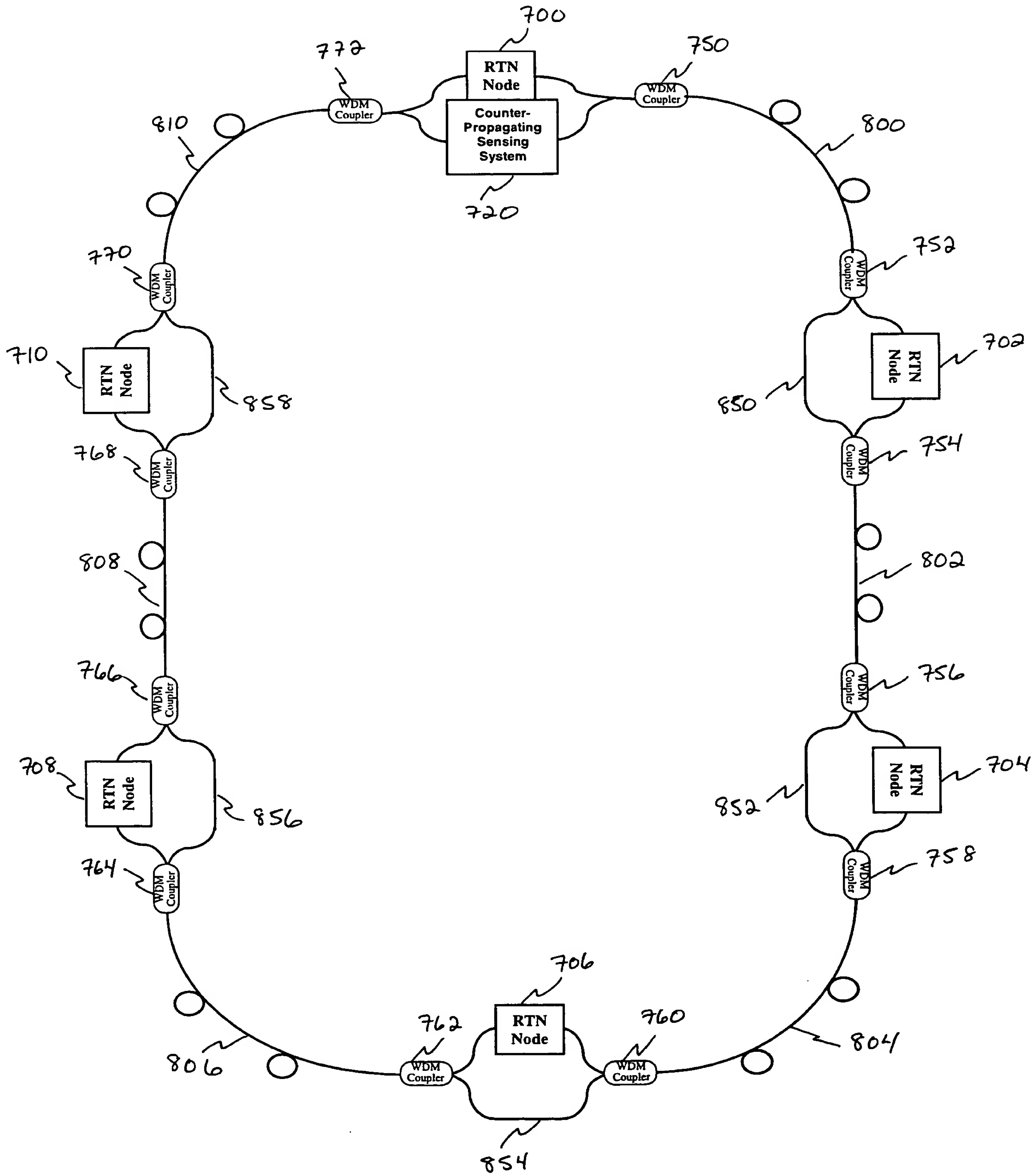

500
RTN Node
572
WDM Coupler
550
WDM Coupler
Sensing Tx
520
Sensing Rx
540
610
600
552
WDM Coupler
570
WDM Coupler
658
502
RTN Node
510
RTN Node
650
554
WDM Coupler
568
WDM Coupler
602
608
566
WDM Coupler
556
WDM Coupler
656
504
RTN Node
508
RTN Node
652
558
WDM Coupler
564
WDM Coupler
506
RTN Node
562
WDM Coupler
560
WDM Coupler
606
604
654

Figure 16


700
RTN Node
Counter-Propagating Sensing System
720
772
WDM Coupler
750
WDM Coupler
810
800
770
WDM Coupler
752
WDM Coupler
710
RTN Node
858
702
RTN Node
850
768
WDM Coupler
754
WDM Coupler
808
802
766
WDM Coupler
756
WDM Coupler
708
RTN Node
856
704
RTN Node
852
764
WDM Coupler
758
WDM Coupler
706
RTN Node
762
WDM Coupler
760
WDM Coupler
806
804
854